

EVALUATING THE EFFECTS OF SNOWSTORM
FREQUENCY AND DEPTH ON SKIER
BEHAVIOR IN BIG COTTONWOOD
CANYON, UTAH

by

Paris Walker Latham

A thesis submitted to the faculty of
The University of Utah
in partial fulfillment of the requirements for the degree of

Master of Science

Department of Geography

The University of Utah

December 2017

Copyright © Paris Walker Latham 2017

All Rights Reserved

The University of Utah Graduate School

STATEMENT OF THESIS APPROVAL

The thesis of _____ **Paris Walker Latham** _____

has been approved by the following supervisory committee members:

_____ **Thomas J. Cova** _____, Chair _____ **12/12/14**
Date Approved

_____ **Simon Brewer** _____, Member _____ **12/12/14**
Date Approved

_____ **Ran Wei** _____, Member _____ **12/12/14**
Date Approved

and by _____ **Andrea R. Brunelle** _____, Chair/Dean of

the Department/College/School of _____ **Geography** _____

and by David B. Kieda, Dean of The Graduate School.

ABSTRACT

Vehicular traffic to the resorts in Big Cottonwood Canyon, Utah during the winter season can be heavy on weekends and mornings just after or during a storm event as fresh snow attracts a large skier population. Traffic congestion can occur given that the canyon road is one lane in each direction, which can have a considerable impact on travel time and associated delays. Despite this condition, no known studies have been conducted to examine relationships between traffic congestion and external environmental factors such as snowstorm depth, time since the previous storm, and time of the winter season. The goal of this research is to articulate some of these relationships using Big Cottonwood Canyon, Utah as a case study. Daily traffic patterns provided by the Utah Department of Transportation (UDOT) are compared to each other in order to identify similarities among them. Characteristics of similar daily traffic patterns such as day of week, base depth, days since prior storm event, and storm depth are explored for potential relationships and to identify common variables between days with like vehicle counts. Daily traffic flows are then analyzed using a bootstrapping method to test the research hypothesis that morning traffic to resorts in Big Cottonwood Canyon significantly increases after a snow event.

TABLE OF CONTENTS

ABSTRACT	iii
LIST OF TABLES	vi
LIST OF FIGURES	vii
ACKNOWLEDGMENTS	ix
Chapters	
1 INTRODUCTION	1
1.1 Problem Statement	2
2 LITERATURE REVIEW	4
2.1 Climate Change and Ski Trends	4
2.2 Cluster Analysis Technique	6
2.3 Significance Testing.....	7
3 STUDY AREA, DATA, AND METHODS	8
3.1 Study Area	8
3.2 Datasets and Date Preparation	9
3.2.1 Seasonal Base Depth.....	10
3.2.2 Storm Event, Accumulation, and Frequency	10
3.2.3 Hourly and Daily Traffic Counts	11
3.3 Methods.....	14
3.3.1 Cluster Analysis Technique	14
3.3.2 Median Resampling	15
4 RESULTS	17
4.1 Hierarchical and K-Means Clustering	17
4.1.1 2007–2008 Winter Season	18
4.1.2 2008–2009 Winter Season	23
4.1.3 2009–2010 Winter Season	25

4.1.4 2010–2011 Winter Season	28
4.1.5 2011–2012 Winter Season	32
4.2 Median Analysis	34
4.2.1 2007–2008 Winter Season	35
4.2.2 2008–2009 Winter Season	37
4.2.3 2009–2010 Winter Season	40
4.2.4 2010–2011 Winter Season	42
4.2.5 2011–2012 Winter Season	44
 5 DISCUSSION	 48
5.1 Characteristics of Seasonal Clusters	48
5.1.1 2007–2008 Winter Season	48
5.1.2 2008–2009 Winter Season	49
5.1.3 2009–2010 Winter Season	51
5.1.4 2010–2011 Winter Season	52
5.1.5 2011–2012 Winter Season	54
5.2 Testing Significance Between Day of Week and Presence of Storm	55
 6 CONCLUSION	 58
 REFERENCES	 59

LIST OF TABLES

Tables

4.1 2007–2008 Median Cluster Measures Per Winter Variable	22
4.2 2008–2009 Median Cluster Measures Per Winter Variable	25
4.3 2009–2010 Median Cluster Measures Per Winter Variable	28
4.4 2010–2011 Median Cluster Measures Per Winter Variable	31
4.5 2011–2012 Median Cluster Measures Per Winter Variable	35

LIST OF FIGURES

Figures

3.1 Study area.....	9
3.2 Distribution of seasonal base depth over each season.	10
3.3 Distribution of daily traffic counts by each season.....	13
4.1 Correlation plot of traffic counts with temporal and seasonal variables.	18
4.2 2007–2008 cluster prototype for hourly vehicle count distribution.....	19
4.3 2007–2008 distribution of cluster observations by day of week.	20
4.4 2007–2008 boxplot of cluster distribution per winter variable.....	20
4.5 2008–2009 cluster prototype for hourly vehicle count distribution.....	22
4.6 2008–2009 distribution of cluster observations by day of week	23
4.7 2008–2009 boxplot of cluster distribution per winter variable.....	24
4.8 2009–2010 cluster prototype for hourly	26
4.9 2009–2010 distribution of cluster observations by day of week.	26
4.10 2009–2010 boxplot of cluster distribution per winter variable.....	27
4.11 2010–2011 cluster prototype for hourly vehicle count distribution.	29
4.12 2010–2011 distribution of cluster observations by day of week.	30
4.13 2010–2011 boxplot of cluster distribution per winter variable.....	30
4.14 2011–2012 cluster prototype for hourly vehicle count distribution.	32
4.15 2011–2012 distribution of clusters by day of week.	33
4.16 2011–2012 boxplot of cluster distribution per winter variable.....	34

4.17 2007–2008 median hourly traffic comparison between weekdays and weekends. ...	36
4.18 2007–2008 median hourly traffic comparison between weekdays with and without a storm event.....	36
4.19 2007–2008 median hourly traffic comparison between weekend days with and without a storm event.....	37
4.20 2008–2009 median hourly traffic comparison between weekdays and weekends. ...	38
4.21 2008–2009 median hourly traffic comparison between weekdays with and without a storm event.....	39
4.22 2008–2009 median hourly traffic comparison between weekend days with and without a storm event.....	39
4.23 2009–2010 median hourly traffic comparison between weekdays and weekends. ...	40
4.24 2009–2010 median hourly traffic comparison between weekdays with and without a storm event.....	41
4.25 2009–2010 median hourly traffic comparison between weekend days with and without a storm event.....	42
4.26 2010–2011 median hourly traffic comparison between weekdays and weekends. ...	43
4.27 2010–2011 median hourly traffic comparison between weekdays with and without a storm event.....	43
4.28 2010–2011 median hourly traffic comparison between weekend days with and without a storm event.....	44
4.29 2011–2012 median hourly traffic comparison between weekdays and weekends. ...	45
4.30 2011–2012 median hourly traffic comparison between weekdays with and without a storm event.....	46
4.31 2011–2012 median hourly traffic comparison between weekend days with and without a storm event.....	46

ACKNOWLEDGMENTS

Thank you first and foremost to my very patient advisor, Tom Cova. Additional thanks to Simon Brewer for all the technical support and to Ran Wei for review and editing assistance. Special thanks to my family and friends for being there for me throughout the process.

CHAPTER 1

INTRODUCTION

Utah's Wasatch Mountain Range is a local, national, and international ski destination that boasts "the greatest snow on earth." As such, Utah has experienced enormous growth within the ski-recreation industry. Recent industry-related annual revenue is estimated at \$1 billion statewide (Wikstrom Economic & Planning Consultants, 2008). Skier days, defined by the U.S. Forest Service as one person visiting a ski area for all or any part of a day for the purpose of skiing, totaled 4.2 million during Utah's 2010-2011 season. This continues a general trend in industry growth and represents a 4% increase in skier days from the previous season, marking the second-best visitor year on record in the state ("Kottke National End of Season Survey 2010/2011," 2011).

Increases in skier days result in corresponding increases of aggregate vehicle trips to ski resorts, and can result in traffic congestion on resort access roads. The Utah Department of Transportation (UDOT) reports that Little Cottonwood Canyon (LCC) experiences average annual daily traffic (AADT) of 5,625 vehicles traveling up-canyon with peak vehicle counts occurring on weekends or holidays during winter months and measured around 12,300 vehicles. Big Cottonwood Canyon (BCC) peak counts hover just above 10,000 vehicles. Hourly traffic counts on peak days in LCC reveal that flow

maximum occurs between 8:00 a.m. and 10:00 a.m., during which approximately 1,100 cars enter LCC in each 60-minute time-interval (Fehr and Peers Associates, 2006).

Skiers can wait several hours in up-canyon traffic queues on the busiest days. On rare occasions, canyon roads may experience periods of congestion-saturation in which vehicle counts are dense enough to cause canyon closure to uphill traffic. For example, on President's Day in 2011, access was closed midmorning in both BCC and LCC due to safety concerns associated with stand-still gridlock and atcapacity resorts (Lee, 2011). While AADT has remained relatively constant over the past 2 decades, regional traffic studies reveal increased frequency of peak days with greater hourly vehicle counts of morning hours. Traffic managers suggest that statewide growth of skier days will continue to influence congestion to resorts, particularly during peak morning hours (Fehr and Peers Associates, 2006).

1.1 Problem Statement

Key factors that affect skier visitation rates to resorts in Utah are snow reliability and quality. Snow reliability is defined in terms of a resort's capacity to remain open. Scott et al. (2003) define snow reliability using measures that result in resort closure, for example snow depth less than 30 cm, 2 consecutive days with minimum temperatures of 50 Fahrenheit *and* liquid precipitation, or liquid precipitation over 2 days totaling 20 mm or more. Snow quality, a normative measure, is much more difficult to empirically quantify; however, a recent survey found that roughly 35% of skiers visiting Utah identify snow quality as the most important factor influencing their destination choice (Wikstrom Economic & Planning Consultants, 2008). It has been shown that diminished seasonal precipitation, snowline creep, and accelerated spring melt will lead to losses of

skiable area, truncated seasons during which resorts can profitably and feasibly run, and an overall reduction in skier visitation and tourism (Yang & Wan, 2010).

Due to the significance of ski tourism to Utah's economy, the state has commissioned several reports over the past decade intended to provide market insight. Surprisingly, only one explores the relationship between snow depth and ski visitation beyond brief acknowledgment that the former influences the latter (Spendlove et al., 2006). No research articles were found that investigate the effects of storm frequency and depth on skier travel behavior and associated congestion to resorts.

Given the recurring seasonal issues with canyon congestion, this research seeks to assess canyon traffic patterns and how they relate to variation seasonal weather and environmental attributes. Large storm events often lead to heavy travel on Utah state road 190 (SR-190), but the temporal nature of traffic responses to storm events has not been studied in any great detail. The primary research goals that will be pursued in this thesis are as follows:

1. Identify any meaningful relationships between seasonal variables and resulting traffic patterns.
2. Determine significant relationships between vehicle counts traveling to resorts on days with snow events compared to days without snow events.

CHAPTER 2

LITERATURE REVIEW

2.1 Climate Change and Ski Trends

Temperature has increased significantly in the western U.S. over the past 50 years (Hamlet & Lettenmaier, 2007). Scenarios put forth by the IPCC project an overall decrease in precipitation in the southwest and mountain west, albeit with heightened event intensity (IPCC, 2007). How temperature increases affect precipitation rates is difficult to determine, due in part to large historical interannual variability of precipitation in the western U.S. As such, research on snowpack and hydrological resources in the region primarily focuses on potential impacts of warming on changes in snowline elevation, and commencement and rate of spring melt (Abatzoglou, 2011; Bales et al., 2006; Barnett, Adams, & Lettenmaier, 2005; Minder, 2010; Mote et al., 2005).

Climate change models of the western U.S. show negative effects on the seasonal snow pack in the Wasatch Range (Abatzoglou, 2011; Mote et al., 2005). Elevations historically delimiting the lower extent of the perennial snowpack will experience a decline in the proportion of precipitation falling as snow (Knowles et al., 2006). A recent model of temperature variation impacts on Wasatch snowfall suggests that an increase of 1° C will result in up to 20% of snow falling as rain, and up to 70% of snow falling as rain

with a rise of 4° C (Jones, 2010). The shift of at- or below-freezing temperatures to higher altitudes is a phenomenon known as *snowline creep* (Mote et al., 2005).

Skiing relies heavily on weather conditions to generate favorable and enjoyable recreation opportunities (Gilbert & Hudson, 2000; Shih, Nicholls, & Holecek, 2009). In a ski survey commissioned by the State of Utah, 35% of skiers visiting the Wasatch Mountains report snow quality as the most important factor when choosing to travel to Utah (Wikstrom, 2007). Tourists for whom snow quality is the primary influence on destination choice represent a considerable proportion of the market, constituting roughly 647,000 of the 4.2 million ski days spent in the state in a given year (Spendlove et al., 2006).

Research on the effects of climate change on ski areas began several decades ago, the earliest papers being published in the 1980s (Harrison et al., 1986; McBoyle & Wall, 1987). Since then, a multitude of regional studies have emerged that measure the influence of seasonal snowfall on skier participation (Breiling & Charamza, 1999; Elsasser & Messerli, 2001; Galloway, 1988; Koenig & Abegg, 1997; Scott et al., 2006). The most common method has been to use ticket sale records in a revealed preference approach, often showing a significant decrease in annual ticket sales associated with reductions in seasonal snowpack (Elsasser & Messerli, 2001; Scott & McBoyle, 2007; Shih, Nicholls, & Holecek, 2008). Such studies have coarse temporal resolution, examining the effects of poor snow quality on an interseasonal basis. Significantly less research exists on stated preference and accompanying resort choice and participation behavior, but has been identified as an important area for further research (Pickering, Castley, & Burt, 2010; Scott, Dawson, & Jones, 2008; Scott & McBoyle, 2007;

Unbehaun et al., 2008; Vivian, 2011).

2.2 Cluster Analysis Technique

Traffic research and modeling has developed rapidly in the past few decades. The rapid expansion of innovative traffic data gathering capabilities has allowed for a growing number and type of traffic studies, and collection methods are ever-expanding. Despite the increase in the quality and granularity of data, typical methods of reporting traffic counts (e.g., AADT) do not capture the complexities of daily traffic flows, and there is a continuing need for systematic analyses that capture the complexities of traffic behavior with a greater temporal resolution (Alvarez, Hadi, & Zhan, 2010). Fehr and Peers Associates (2006) state an outstanding need for in-depth analysis of peak demand traffic volumes in the Cottonwood Canyons.

There are currently an abundance of approaches to temporally resolute traffic analysis. One such method is the cluster analysis technique. Cluster analysis is a statistical technique that has been developed for effective classification of observational objects into homogeneous groups, or clusters (Anderberg, 1973). There exist two basic algorithmic methods for clustering: partitioning and hierarchical algorithms (Kaufman & Rousseeuw, 1990). The hierarchical method is optimal for traffic research due to the fact that the hierarchical technique does not require specification of the number of data clusters in advance to cluster assignment, but instead follows from exploring data via dendrograms. Considering both shape and height of a 24-hour traffic count over the observational period, a profile is established that reflects a cluster prototype, or center, that allows for cluster partitioning.

The Traffic Monitoring Guide (FHWA, 2001) has previously recognized the need

for derivation of traffic patterns that use pattern-matching methods, a category into which cluster analysis falls. Early applications of cluster analysis have been employed by both Wild (1997) and Chung (2003). Their analyses focus on travel times as opposed to travel demand, and are challenging to interpret or summarize (Soriguera, 2012). Wijermars and van Berkum (2005) used a preclassification method for design of a traffic clustering algorithm, but the focus on capturing daily traffic demand variation overlooks potential seasonal variations. Soriguera (2012) recognizes the need for a more tolerant analysis and seeks to modify existing methodologies to incorporate seasonal considerations. His framework is applicable to traffic forecasting and is a sound basis for analysis of fluctuating traffic-flows, but does not consider variables associated with event-based traffic responses.

2.3 Significance Testing

Bootstrapping, a method developed for evaluating replicability of data, was originally presented by Efron (1979). Thompson (1993) conceptually describes the bootstrapping method as copying the dataset many times while resampling from the original dataset with replacement. Results can be computed distinctly from each sample, and averaged. Using stratified sampling, data can be grouped into subsets so that resampling occurs only between the data points within that subset. Stratified sampling is important in time series analysis in that it enables resampling to occur between data points belong to a subset with specific criteria, such data points occurring on weekdays versus weekends. This allows subsets meeting varying criteria to be tested for significant differences from other subsets, or to the dataset as a whole.

CHAPTER 3

STUDY AREA, DATA, AND METHODS

This chapter outlines the principal steps of data and model development required for the purpose of this research. Traffic and weather data for model input were collected from Natural Resource Conservation Service Snow Telemetry (SNOTEL) sites in Utah, the Utah Department of Transportation (UDOT), and the Alta Department of Transportation (Alta DOT). Datasets were then merged to fulfill requirements for model input. Data analysis and presentation were accomplished using the R Statistical Software (R Core Team, 2013). This chapter begins with a brief narrative of the study area, followed by a description of data preparation, and finishes with an explanation of the methods used for data analysis.

3.1 Study Area

The area of study for the application of this research is located in Big Cottonwood Canyon in Utah's Wasatch Range within the Wasatch-Cache National Forest, east of and adjacent to Salt Lake City's metropolitan district and displayed in Figure 3.1. Big Cottonwood Canyon experiences high storm counts during the winter season, and as a result can suffer from traffic congestion of those seeking to pursue winter recreation opportunities as a result of storms. This research uses automated hourly traffic counts collected at the base of Big Cottonwood Canyon. The traffic counter, operated by the

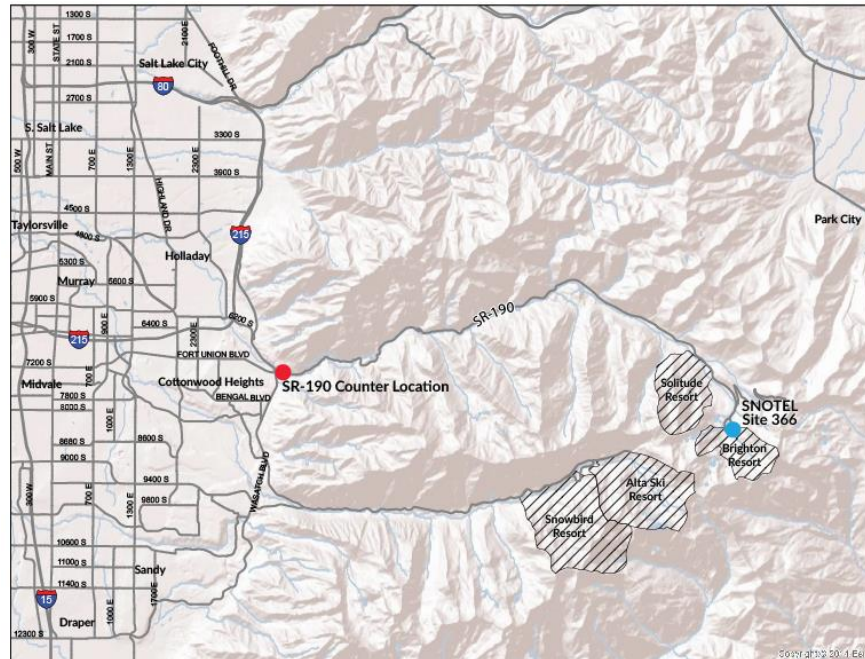


Figure 3.1 Study area.

Utah Department of Transportation, is located at the entrance to Big Cottonwood Canyon on Utah State Route 190 (SR-190). With steep canyon topography on either side, SR-190 is predominately limited to one lane of travel in each direction. It provides access to Solitude Mountain Resort and Brighton Resort, the latter at which the road terminates. Guardsman Pass Road, the only other road providing access to SR-224 outside of Park City, is closed during the winter months. No other outlets from SR-190 exist.

3.2 Datasets and Data Preparation

Data were prepared and integrated primarily using Microsoft Excel software. Several data types from a variety of sources were combined into one dataset to facilitate analysis of winter storm patterns, seasonal variables, and potential influence on traffic response. The final dataset includes daily BCC base-depth observations recorded by SNOTEL, 24-hour snow accumulation totals of Alta DOT numbered storm events, and

hourly vehicle counts of cars traveling up-canyon on SR-190. Due to limitations in data availability, a total of five winter seasons were considered in this study. Data characteristics and relationships are analyzed within the R statistical environment using a suite of publicly available statistical packages.

3.2.1 Seasonal Base Depth

SNOTEL data were collected for Site 366 at Brighton, UT. Cumulative data collected by SNOTEL reset to zero on September 1st every year, making the SNOTEL base depth-data ideal for the seasonal nature of this research. Daily snow depth measurements were collected from 2007 onward, represented in Figure 3.2. No manipulation of the data was required, and it was appended into the master dataset in the same format it was delivered.

3.2.2 Storm Event, Accumulation, and Frequency

Storm data determined to be the best option for analysis are monitored and collected at Alta DOT's Guard site, located in LCC (40°35'24.56"N 111°38'16.95"W).

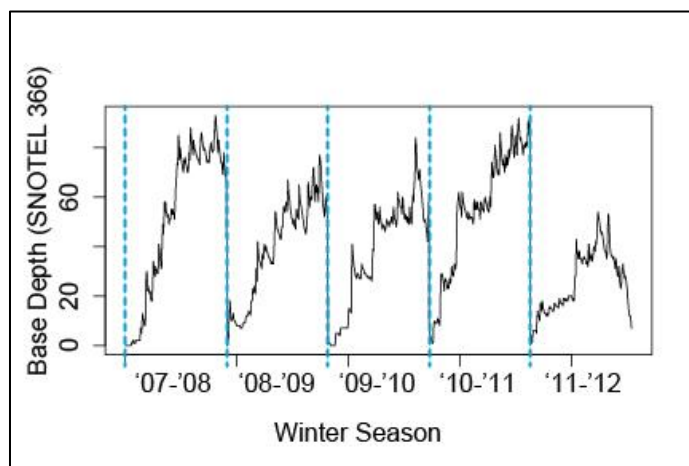


Figure 3.2 Distribution of seasonal base depth over each season.

snowfall due to similarities in snow accumulation and storm duration between the two canyons. Alta DOT records from the Guard site date back to 1983; however, since up-canyon vehicle counts are only available since 2007 to 2012, only storm events within the timeframe constraints of the traffic data are considered. Alta DOT is capable of delivering storm records that detail day of storm, longevity of storm event, and sequential storm event of the winter season. Alta DOT-reported storms are assigned a seasonally cumulative number when considered to be part of a major storm event, allowing for storm-cycles with inconsistent precipitation to be considered within the model. A storm is numbered if 12 inches or more of snow accumulate over any 24-hour period over the duration of the storm-cycle. The snowfall rate does not have to be constant to be numbered, and an event may last several days despite only experiencing the required 12 inch accumulation per 24 hour ratio for one of numbered storm days.

Days between storm events, a variable considered in this research, can be determined from the Alta DOT dataset. Continuity of days without a storm, or those without a numbered storm event, is calculated by assigning a binary-operator of '0' to days that experience a storm event and '1' to days that do not experience a storm event. Positive binary values are summed for periods of time lacking storm events, and cumulative values reset to zero when a storm event occurs. This allows for exploration of duration of nonstorm days (dry spells) as they relate to traffic counts, and associated user-response to Numbered Storm Event given any dry spell.

3.2.3 Hourly and Daily Traffic Counts

UDOT has traffic counts records on SR-190 (UDOT Site 322) since 1985. Evaluating user-response to snow events requires that traffic count data differentiates

between up-canyon (positive) and down-canyon (negative) travel. For the purpose of this research, only the positive counts are considered. Records delineating between positive and negative are available from 2007 onward. For the purpose of this research, a winter season begins on November 1st and ends on April 30th; at the time of data collection, five complete datasets were available.

There are several missing days of traffic counts within the study timeframe. Missing traffic observations were interpolated in order to fully examine the relationship of seasonality on traffic patterns on SR-190. Missing values are imputed using existing vehicle count data within the time constraints of the study and that meet specific criteria including day of week and presence or absence of storm event, exceptions being made for imputation of holiday vehicle counts. Traffic observations used to interpolate missing values were required to be within a +/- 2 week window of the month and day of the missing values, but could be from a different year within the study time frame. Missing data values are interpolated by averaging same day-of-week for all available data points within the +/- time envelope of the missing data point. For example, a missing data value occurring on a Saturday is interpolated by averaging available traffic counts recorded on Saturdays within the averaging window. Long-term traffic patterns focusing on explicit demand behaviors have been addressed in traffic research. Through such research, it has been well established that weekdays and weekends can and should be considered differently (Weijermars & van Berkum, 2005). The distribution of traffic counts is represented in Figure 3.3.

When calculating proxy values, it is necessary to consider if a count used for averaging occurs during an Alta DOT Numbered Storm Event. Missing values that occur

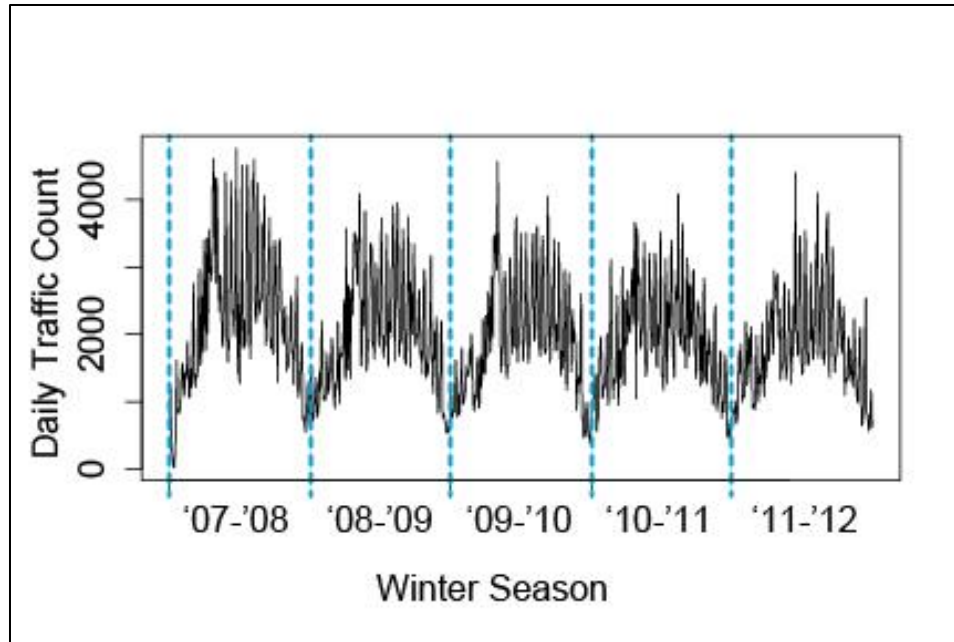


Figure 3.3 Distribution of daily traffic counts by each season.

during a Numbered Storm Event are averaged only with other Numbered Storm Events occurring on the same day-of-week and within the allocated time envelope. This method is used to accurately capture potential differences in user behavior that are contingent on day-of-week and presence or lack of storm event.

Exceptions to this general method were applied to holidays and holiday weekends. Traffic dynamics on and around holidays, specifically those occurring on weekends, are known to have different patterns than nonholiday traffic. Holidays and holiday weekends that are within the extent of and considered for this study are Thanksgiving Day through Thanksgiving weekend, Christmas Day through New Year's Day, Martin Luther King Jr. Day weekend, Presidents' Day weekend, and Easter Sunday weekend. Available proxy data used to interpolate traffic patterns occurring on these holidays and holiday weekends average only the same day-of-week with the identical temporal relationship to that holiday, maintaining only the consideration of presence or

absence of storm event.

3.3 Methods

3.3.1 Cluster Analysis Technique

The dataset is stored as a matrix wherein each row represents 1 day of data observations. Each row has 24 hours of traffic counts, the sum of daily traffic counts, as well as the month of the winter season (e.g., November is month 1), the day of the week, presence or absence of storm event, the depth of the storm event, number of days since the previous storm, and the base depth of snow as reported by SNOTEL for site 366. A hierarchical clustering method is employed to determine k-means groups for each winter season in the dataset. In essence, the hierarchical method computes the difference between observations or, in this case, groups of daily observations recorded at hourly intervals. Through this process, more similar objects are identified and agglomerated together. The result can be represented in a dendrogram that reveals the hierarchical structure of the data grouping.

Using the *hclust* hierarchical clustering function in R, a dendrogram visualization of the seasonal datasets is used to determine and manually apply the optimal value of k-means clustering partitions. The *hclust* function clusters daily traffic data by employing a set of dissimilarities by which hourly traffic distributions are compared. To begin, each object is partitioned into a unique cluster. The most similar clusters are joined throughout sequential iterations of the function until all objects are joined into a single cluster. Object similarity uses the mean of the distances between all points in two clusters to analyze the overall similarity. Each day within a seasonal dataset is clustered manually using a hierarchical graph-based cluster method. Once suitable cluster groups are

identified, the data are partitioned into cluster groups using k-means prototype clustering and a Euclidean distance metric.

It is possible to use the cluster groupings to conduct exploratory analysis among the different variables. Cluster distributions are examined in a histogram to see counts per day of week. They are also explored as they are dispersed against base depth, storm depth, and days since the previous storm. Storm depth is considered to be accumulation (in inches) that occurs from 4:00 am the previous day to 4:00 am on the day of traffic observations.

3.3.2 Median Resampling

A permutation test is used to test for significant differences within the dataset. Each season, bounded by November 1st and April 30th, is considered separately from each other. Daily blocks are grouped into subsets, and significance between subsets is tested. Three tests are run on the data. Data are tested for significant differences between weekday and weekend, weekday with a storm event and weekday without a storm event, and weekend with a storm event and weekend without a storm event. By using daily blocks for significance testing rather than resampling hourly traffic count data, the method inherently accounts for autocorrelation.

For the first test, data are grouped into weekdays and weekends. Differences of median hourly traffic count by daily block are calculated for weekdays and weekends using the resampling method over 1000 iterations. For the first significance test, presence or lack of snow event is ignored. Weekdays are then put into subgroups determined by the snow event variable. Again, resampling within and difference testing between the subgroups is conducted over 1000 iterations. This same process is run on

weekend traffic counts, again subgrouped by presence of the snow event variable. If no significant difference exists between groups, the mean of resampled medians will be normally distributed around zero. Comparing this distribution with the observed median difference allows an assessment of the probability of that value occurring randomly.

CHAPTER 4

RESULTS

This chapter provides an overview of the clustering results of daily traffic patterns on SR-190 followed by the results of median resampling method on seasonal traffic. Results are reported by winter seasons bounded by November 1st and April 30th for each season of study, of which there are five. Figure 4.1 depicts the correlation between all variables considered in this study.

4.1 Hierarchical and K-Means Clustering

Data were clustered by season to account for any variations in visitation patterns that are unique to an individual season. Beginning with the winter of 2007-2008, the hierarchical and k-means clustering technique is applied to each ski season within the range of study and undergoes cluster analysis to summarize seasonal traffic characteristics. Each season is subject to hierarchical and k-means clustering methods through which homogeneous data structures of daily traffic patterns are identified and similar objects are grouped. Days within a season sharing similar hourly traffic count trends are grouped together and distribution of nontraffic variables within the cluster are investigated. For the purpose of this research, relationships within and distributions among seasonal clusters are calculated for the following variables: observations by day of week, base depth of seasonal snowpack (base depth), accumulation of snow during a

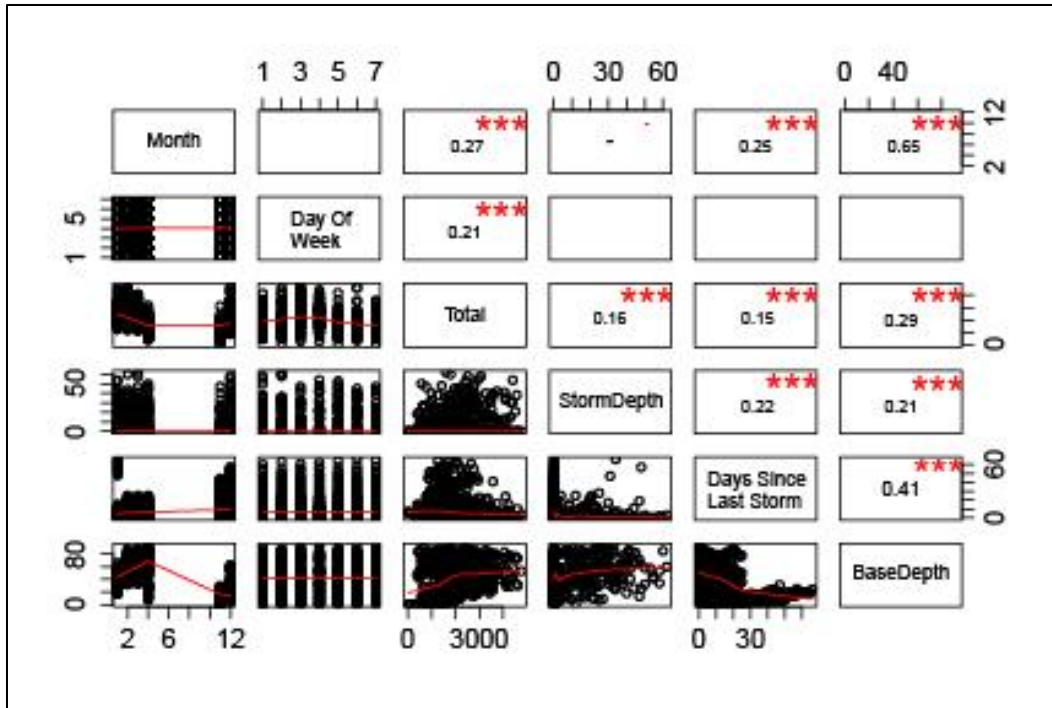


Figure 4.1 Correlation plot of traffic counts with temporal and seasonal variables.

storm event by 24-hour intervals (storm depth), and number of days since previous storm event (time to storm).

4.1.1 2007–2008 Winter Season

Numbered storm days comprise 27.6% of total seasonal days within the 2007-2008 ski-season. The 2007-2008 season is clustered into four groups. Cluster prototypes 1 through 4 follow a similar function, but at varying amplitudes. Figure 4.1 shows the distribution of hourly vehicle counts for cluster prototypes for the 2007-2008 season.

Cluster group 3 is shown to capture days with the highest amplitude of hourly traffic counts, followed by group 1, group 2, and finally group 4 (23 observations of which occur during the first 23 days of November, and 10 of which occur sequentially during the last 10 days of April).

Cluster group 1 sees peak number of observations on Sunday, followed by Saturday. Cluster group 2 is uniformly distributed among all weekdays, with a slight peak on Thursday and the fewest observations on Sunday. Cluster group 3 has its mode on Saturday, with very few counts occurring midweek. Cluster group 4 has peak observations on Wednesday, with weekends having the fewest observations. Figure 4.2 shows the distribution of hourly vehicle counts for cluster prototypes for the 2007-2008 season while Figure 4.3 displays the distribution over the day-of-week distribution that cluster prototypes fulfill.

Illustrated in Figure 4.4, the median base depth during the 07-08 season is 65.0". Cluster group 2 has the highest median base depth at 73.5" and the smallest variance. Group 3 has a median base depth of 58" and the second smallest range in base depths within the cluster. Group 1 has a median base depth of 53" and the second largest range

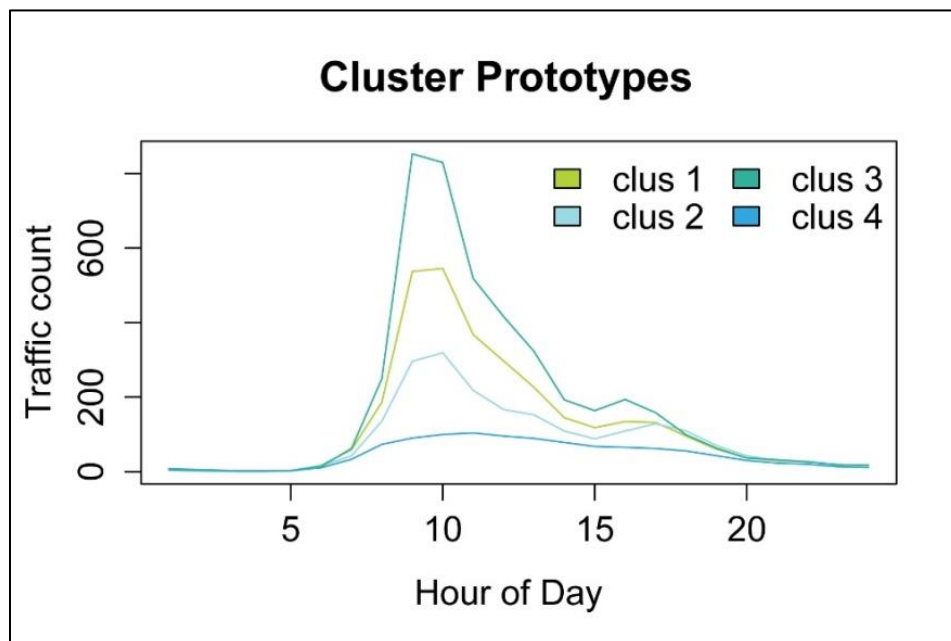


Figure 4.2 2007–2008 cluster prototype for hourly vehicle count distribution.

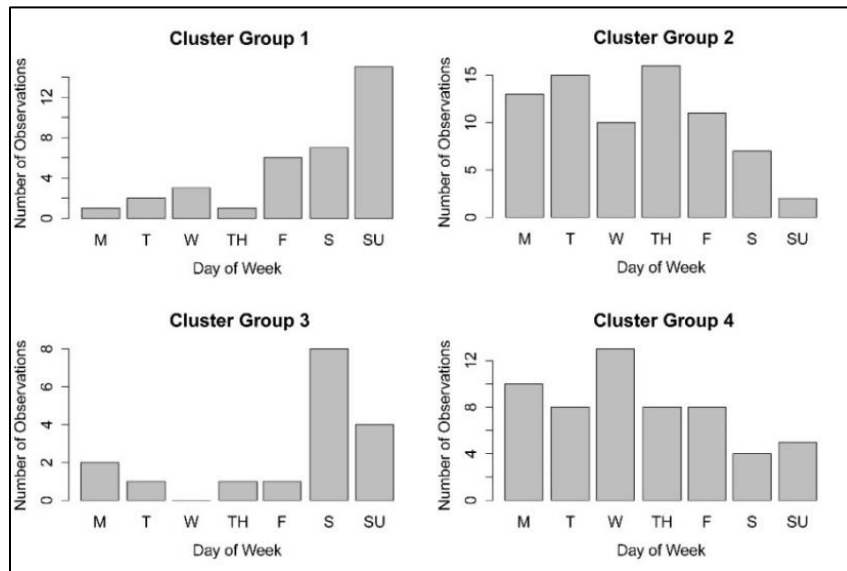


Figure 4.3 2007–2008 distribution of cluster observations by day of week.

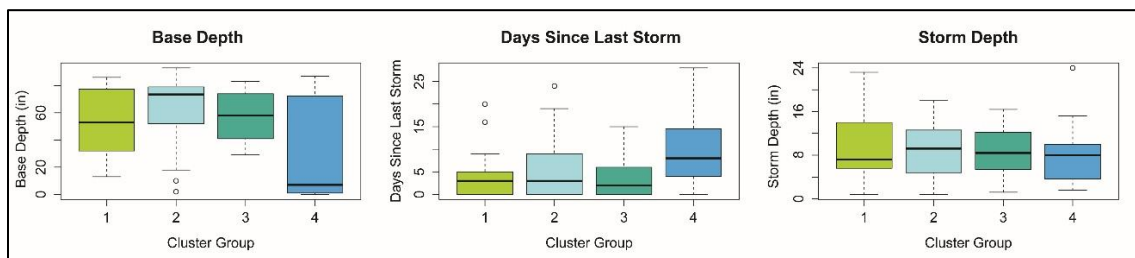


Figure 4.4 2007–2008 boxplot of cluster distribution per winter variable.

of base depth values. Group 4 has the smallest median base depth, measured at 7", and has the greatest variance of base depth values.

In the 07-08 season, there are 51 days considered to be part of a numbered storm, representing 27.6% of total study days within the season. Group 1 counts 15 numbered storm days and has the highest percentage of 43.0% numbered storm days within the group. Group 2 has the highest count of numbered storm days at 19, but storm days represent 26.0% of group observations. Group 3 has 7 storm days, but storm days represent a high percentage of observations at 41.0%. Group 4 has 9 storm days that comprise only 16% of total observations within the cluster. The median 24-hour storm depth during the course of the season is 9.0". Among the clusters, group 1 has the greatest median storm depth of 9.7", followed by group 4 with a median of 9.0", group 2 with a median of 8.8", and finally group 3 with a median of 8.6".

The seasonal median of days between storm events is 4.0. With a median of 7.5, group 4 shows the longest time between storm events. Group 1 and 2 have a median of 3.0 days between storm events, and group 3 has the shortest time between storm events at 2.0 days. Results are summarized in Figure 4.4 and Table 4.1.

The 2008-2009 ski season is clustered into five groups. Cluster prototypes follow a similar function, but at varying amplitudes, displayed in Figure 4.5. Cluster group 5 is shown to capture days with the highest amplitude of hourly traffic counts, followed by group 1, group 3, group 2, and finally group 4 (11 observations of which occur consecutively on the first 11 days of the season and 11 of which occur consecutively on the last 11 days of the season).

Table 4.1
2007–2008 Median Cluster Measures Per Winter Variable

Cluster	No of Observations	Types of Days	Median Base Depth (in)	% of Days That Are Numbered Storm Events	Median Storm Depth (in)	Median Time Between Storm Events
1	35	Weekend days	53.0	43.0%	9.7	3.0
2	74	Weekdays	73.5	26.0%	8.8	3.0
3	17	Saturdays	58.0	41.0%	8.6	2.0
4	55	Weekdays, early and late season	7.0	16.0%	9.0	7.5

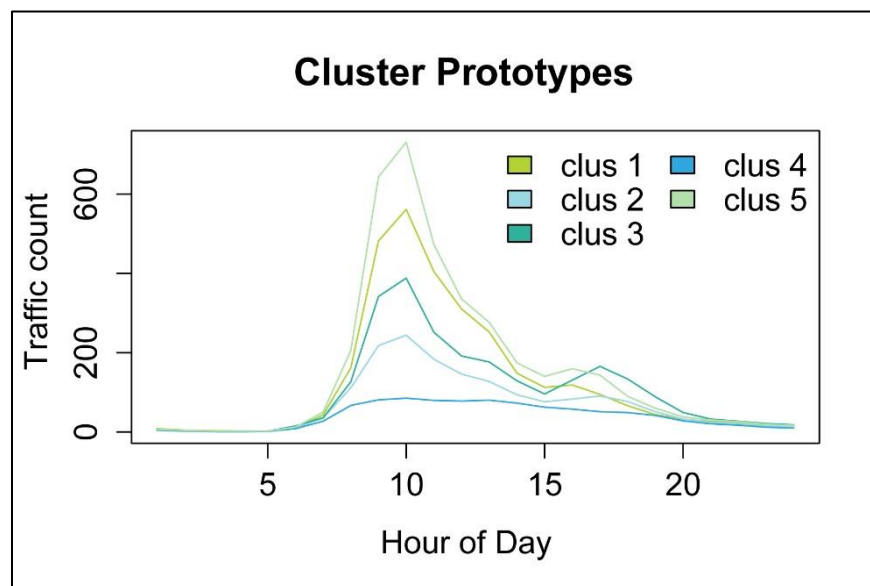


Figure 4.5 2008–2009 cluster prototype for hourly vehicle count distribution.

4.1.2 2008–2009 Winter Season

As portrayed in Figure 4.6, the majority of group 1 observations fall on the weekend with the most observations occurring on Sunday. Group 2 is uniformly distributed among weekdays (Monday through Thursday) with lower observational counts during weekends. Group 3 has a predominate number of observations on Thursday and Friday. Group 4 has peak counts on Monday and Tuesday with weekend days uniformly having the lowest number of observations. Group 5 has the lowest number of observations, with a peak on Sunday.

Median base depth for the season is 45.0". Figure 4.7 indicates that group 3 has the highest median base depth of 54.5". Cluster group 2 has the second highest median

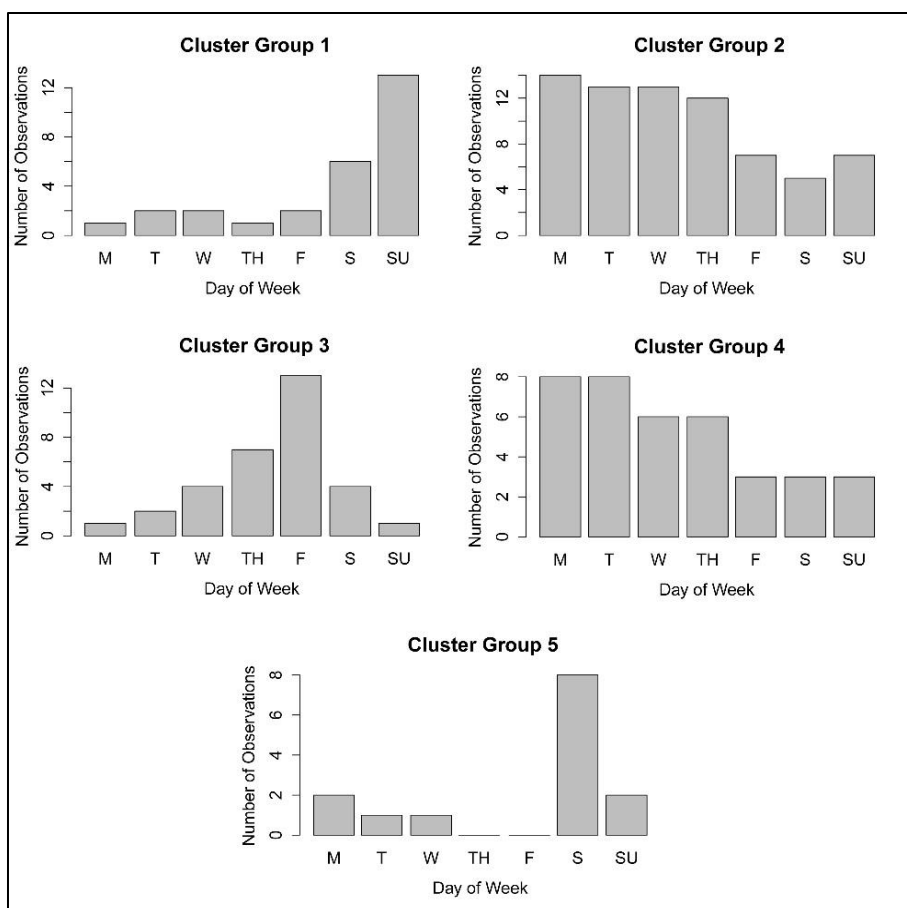


Figure 4.6 2008–2009 distribution of cluster observations by day of week.

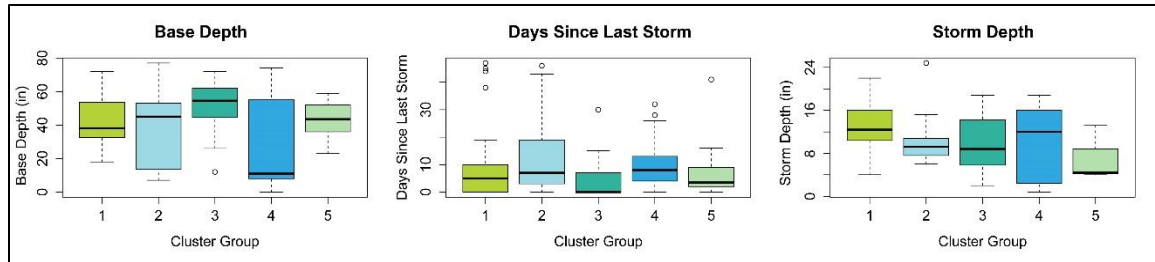


Figure 4.7 2008–2009 boxplot of cluster distribution per winter variable.

base depth with 45.0”. Group 5 represents the middle base depth measurement for the cluster groups with a median base depth of 43.5”. Group 1 follows with a median base depth of 38.0”, and the Cluster group 4 has the lowest median base depth of 11”.

There are 43 numbered storm days in the 08-09 season, representing a seasonal percentage of 23.8% of observational days being considered as part of a storm event, illustrated in Table 4.2. The median storm depth for the season is 9.1”. Twenty-six percent of total observational days within Cluster group 1 account for the greatest median storm depths, measured at 12.2”. Storm days within Cluster group 4 only accounts for 14% of observational days within the group, but have a median storm depth of 11.8”. Group 2 has a median base depth identical to the seasonal average of 9.1”, but numbered storm events represent less than the seasonal proportion at 18.0% of observational days. Group 3 has a median storm depth of 8.7” and the greatest percentage of numbered storm days within a group at 47.0%, well above the seasonal percentage. There is a large drop in average storm depth for Cluster group 5 with a median of 4.3”, numbered storm days of which represent 21.0% of total days within Cluster group 5. Group 3 has the smallest measure of days since the previous storm event, with a median of 0 days. Group 5 follows with a median of days since the previous storm of 3.5. Group 1, group 2, and

Table 4.2
2008–2009 Median Cluster Measures Per Winter Variable

Cluster	No. of Observations	Types of Days	Median Base Depth (in)	% of Days That Are Numbered Storm Events	Median Storm Depth (in)	Median Time Between Storm Events
1	27	Sunday	38.0	26.0%	12.2	5.0
2	71	Weekdays	45.0	18.0%	9.1	7.0
3	32	Thursday and Friday	54.5	47.0%	8.7	0.0
4	37	Weekdays	11.0	14.0%	11.8	8.0
5	14	Saturday	43.5	21.0%	4.3	3.5

group 4 follow with medians of 5, 7, and 8 days between storm events, respectively.

4.1.3 2009–2010 Winter Season

The 2009-2010 season clusters into four groups. Group 1 has the highest amplitude of hourly traffic counts for observations included in that group. Group 2 has the second highest amplitude, followed by group 4 and finally group 3. All groups follow a similar daily function, as shown in Figure 4.8.

Group 1 has most observations occurring on Saturday, followed by Sunday. There are no observations in group 1 occurring on Wednesday, Thursday, or Friday. Group 2 also sees most of the group's observations occurring on the weekend, with very few observations occurring during the week. Group 3 is fairly uniformly distributed among all weekdays, including Friday. Cluster group 4 is also fairly uniformly distributed among all weekdays, including Friday. Cluster group distributions are pictured in Figure 4.9.

The median base depth of the season is 48.0". Group 1 has the greatest median

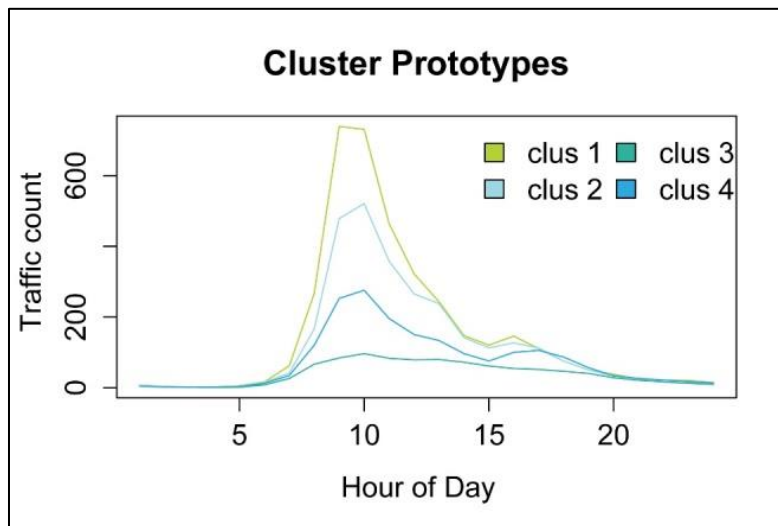


Figure 4.8 2009–2010 cluster prototype for hourly vehicle count distribution.

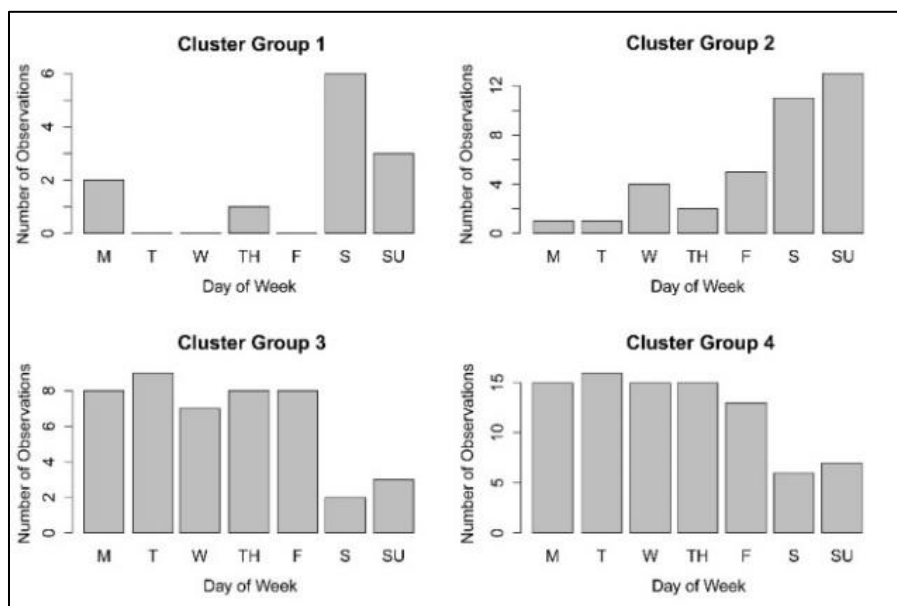


Figure 4.9 2009–2010 distribution of cluster observations by day of week.

base depth of 50.5” and is followed by group 2 and group 4, both of which have a base depth of 49.0”. Group 3 has the lowest median base depth of 7.0”. Group 1 has the smallest range of base depth measures associated with the cluster. Group 2 and group 4 have similar ranges of base depth values, as illustrated in Figure 4.10.

As detailed in Table 4.3, the seasonal percentage of observations coinciding with a numbered storm event is 16.6% and the median storm depth is 7.9”. Group 2 has the greatest median storm depth of 12.6” but simultaneously one of the greatest ranges within the group; Cluster group 2 observations capture just above the seasonal measure of numbered storm days at 18.9%. Group 1 has a much smaller range of measured storm depths within the group and a median storm depth of 9.1”; Cluster group 1 has the greatest percentage of numbered storm days at 41.7%, measuring far above the seasonal proportion. Group 3 has a storm depth median of 8.3” and the largest range of storm depths within the group, but at 8.9% of observational days considered as storm events, it represents the lowest ratio of storm to nonstorm days of the cluster groups. Cluster group 4 has a median of 7.1” per storm event and is approximately equivalent to the season as a whole with respect to the proportion of storm to nonstorm observations with 16.1% of observations within the group categorized within a numbered storm event.

The cluster groups display a broad range of dry periods captured by each group.

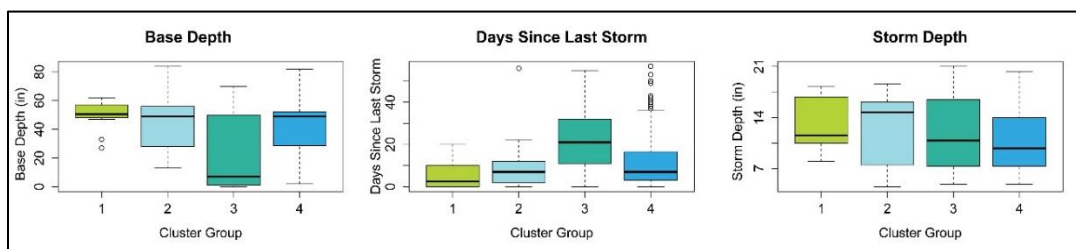


Figure 4.10 2009–2010 boxplot of cluster distribution per winter variable.

Table 4.3

2009–2010 Median Cluster Measures Per Winter Variable

Cluster	No. of Observations	Types of Days	Median Base Depth (in)	% of Days That Are Numbered Storm Events	Median Storm Depth (in)	Median Time Between Storm Events
1	12	Saturdays, Sundays, no Tuesdays, Wednesdays, or Fridays	50.5	41.7%	9.1	2.5
2	37	Weekend days	49.0	18.9%	12.6	7.0
3	45	Weekdays including Friday	7.0	8.9%	8.3	21.0
4	87	Weekdays including Friday	49.0	16.1%	7.1	7.0

Group 1 has the shortest time between storms with a median of 2.5 days. Cluster group 2 and group 4 have the same median of 7 days since the previous storm, but group 4 has a greater group range. Group 3 has the greatest median of 21 days since the previous storm.

4.1.4 2010–2011 Winter Season

The 2010–2011 season has the highest percentage of numbered storm days of seasons within the study, with 33.1% of all days considered to fall within a numbered storm event. The seasonal median base depth is 57” and median days between storm events is 3. Daily traffic observations cluster into 4 groups. Group 1 has the highest amplitude of hourly traffic counts, followed by group 4, group 2, and finally group 3. The clusters follow a similar function despite varying amplitudes, shown in Figure 4.11.

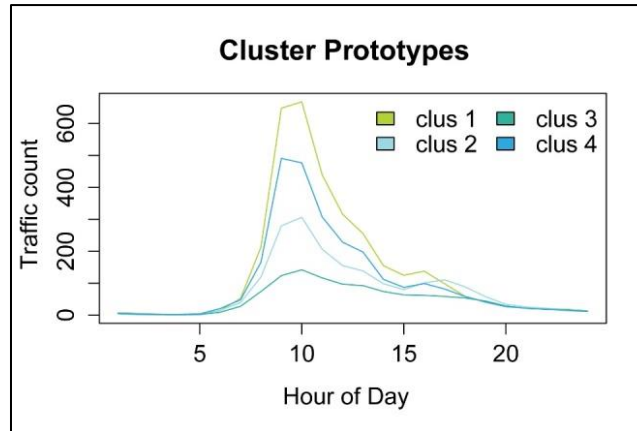


Figure 4.11 2010–2011 cluster prototype for hourly vehicle count distribution.

Figure 4.12 shows that group 1 has a normal day-of-week distribution around Saturdays and all days of the week have some observations except for Wednesdays, which has none. Group 2 has fairly uniform distribution over weekdays (Monday through Thursday) and peak number of observations on Friday. Sunday has the lowest number of observations. Group 3 has fairly uniform distribution over the weekdays (Monday through Thursday) with a drop in observations on Friday and the lowest number of observations on the weekend. Cluster group 4 has peak number of observations on Sunday, followed by Saturday, and very few observations on any of the weekdays.

Several of the groups have similar median base depths. Group 2 has a 58.5” median base depth, followed by group 4 at 58” and group 1 at 56.5”. Group 1 has the smallest range of base depths associated with observational days, while group 2 and group 4 have similar ranges. Group 3 has the lowest median base depth of 40.5” and the largest range of all the cluster groups. Similarities between groups are pictured in Figure 4.13.

The seasonal median storm depth is reported at 5.3”. Measured at 9.8”, cluster

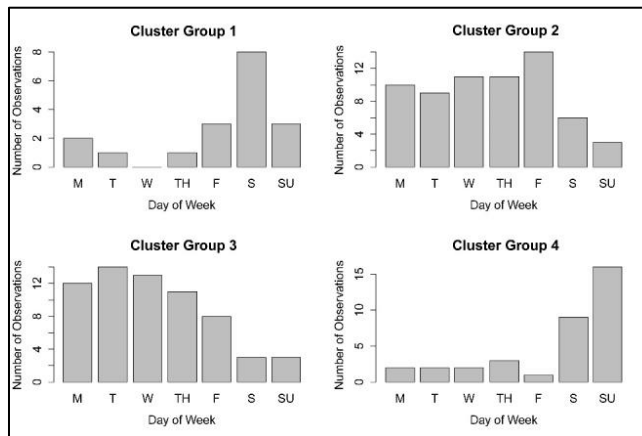


Figure 4.12 2010–2011 distribution of cluster observations by day of week.

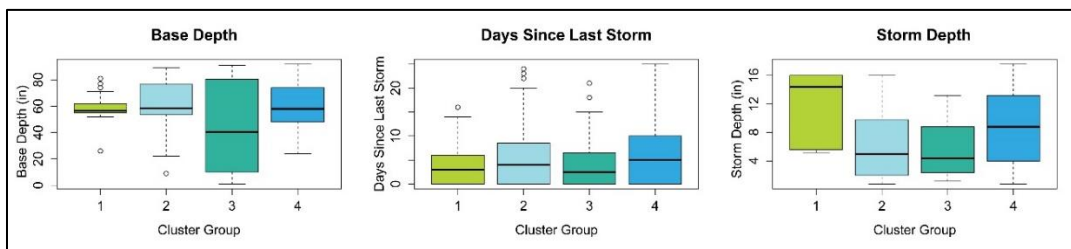


Figure 4.13 2010–2011 boxplot of cluster distribution per winter variable.

group 1 has the greatest median storm depth; group 1 days that classify as a numbered storm event comprised 33.3% of total group observations, approximately equal to the proportion of numbered storm days observed throughout the 2010-2011 ski season. Group 4 has the second greatest median storm depth with 8.7", but the proportion of storm days within the group is found to be greater than that of the season, calculated at 40%. Group 2 has the second lowest median storm depth at 4.92" but represents the cluster group with the lowest ratio of storm to nonstorm days and the only group with a lower proportion of storm days than the season as a whole, measured at 25.0%. Group 3 has the lowest median storm depth of the cluster groups, measured at 3.7"; the proportion of storm to nonstorm days within group 3 is just above the seasonal average at 37.5% of observational days within the group. Details are shown in Table 4.4.

Group 4 has the greatest median number of days between storm events, measured at 5 days. Group 2 follows in longest dry periods with a median of 4 days between storm events. Group 1 and group 3 capture the smallest time between storm events, with

Table 4.4

2010–2011 Median Cluster Measures Per Winter Variable

Cluster	No. of Observations	Types of Days	Median Base Depth (in)	% of Days That Are Numbered Storm Events	Median Storm Depth (in)	Median Time Between Storm Events
1	18	Saturdays, no Wednesdays	56.5	33.3%	9.8	3.0
2	64	Friday and weekdays	58.5	25.0%	4.9	4.0
3	64	Weekdays	40.5	37.5%	3.7	2.5
4	35	Sundays, Saturdays, some weekdays	58.0	40.0%	8.6	5.0

medians of 3 days and 2.5 days, respectively.

4.1.5 2011–2012 Winter Season

The 2011-2012 season has the lowest percentage of numbered storm days, with 15.4% of all days within the season considered to coincide with a classified numbered storm event. The seasonal median base depth is 24.5” and median days between storm events is 10.5 with a maximum of 66 consecutive days without significant snow accumulation. Daily traffic observations cluster into 4 groups. Group 3 has the highest count of hourly traffic, followed by group 2, group 1, and finally group 4. The clusters follow a similar function despite varying amplitudes, shown in Figure 4.14.

Group 1 has a fairly normal distribution of observations around Wednesday, with Saturday representing the fewest observations. Group 2 has peak number of observations on Saturday with the fewest observations midweek. Group 3 has almost all observational

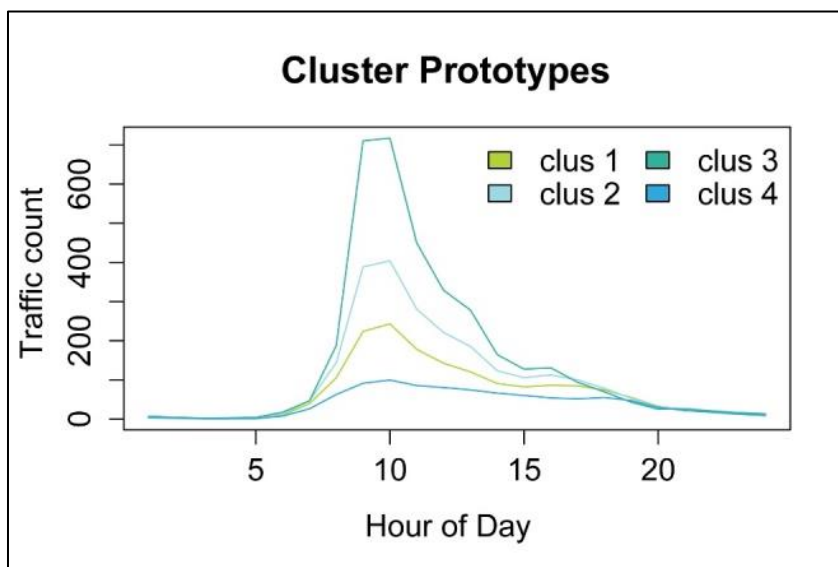


Figure 4.14 2011–2012 cluster prototype for hourly vehicle count distribution.

counts on the weekend, and no observations occurring midweek. Group 4 is relatively uniformly distributed amongst weekdays, with peak number of observations occurring on Tuesday and fewest on weekend days. Distributions are illustrated in Figure 4.15.

As shown in Figure 4.16, group 3 has the greatest median base depth of 38.0” and a very small range within the group. Group 1 has the second greatest median base depth at 31.0” but a much greater range within the cluster. Group 2 has the second lowest median base depth, measured at 28.0”, and a range of base depth values similar to group 1. Group 4 has the smallest median base depth value of 13.0”.

The seasonal median storm depth is measured at 5.5”. Group 3 has the greatest median storm depth of 8.9” but the largest range of storm depths of all the clusters; Cluster group 3 also has the greatest proportion of numbered storm days, well above the seasonal proportion, at 30.8%. Group 1 has the second greatest median storm depth of 6.5” and the smallest range of the clusters, but the proportion of storm days within the group is below the seasonal percentage at 10.4%. Group 2 and group 4 have the same median storm depth of 4.3”. Group 2 has a greater range of storm depths within the

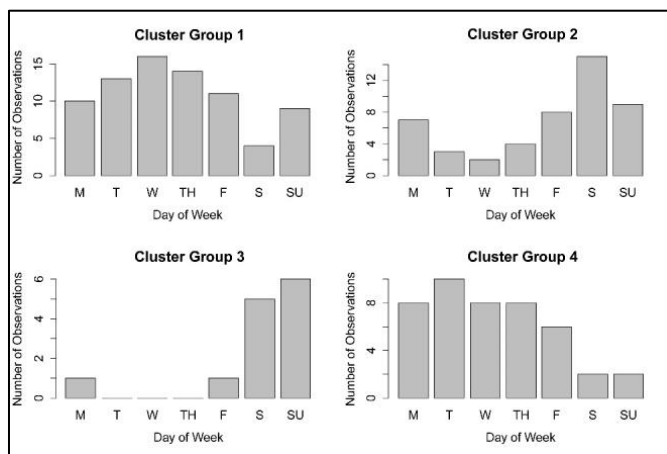


Figure 4.15 2011–2012 distribution of clusters by day of week.

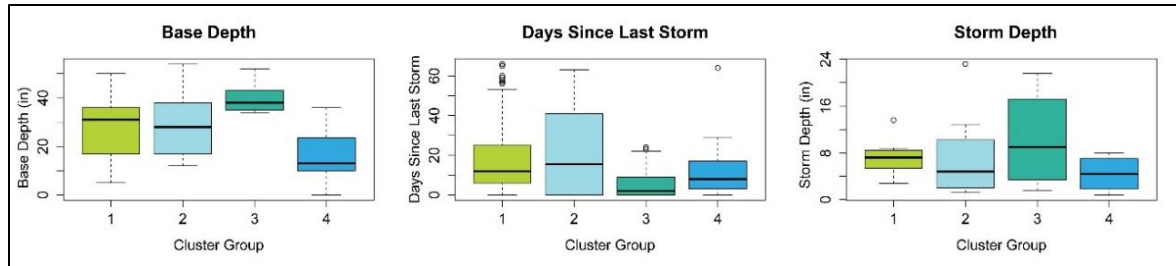


Figure 4.16 2011–2012 boxplot of cluster distribution per winter variable.

cluster and storm days represent a percentage greater than the season, calculated at 25.0%. The percentage of storm days within group 4 represent the lowest within-group proportion, calculated at 9.1%. Table 4.5 provides detail on cluster groups.

Group 2 has the longest median number of days since the previous storm, calculated at 15.5 days, as well as the largest range of time since the previous storm event. Group 1 follows with longest periods between storm events, measured at 12 days. Group 4 has an 8-day median since the previous storm, and group 3 has the smallest median of time since the previous storm event, calculated at 2 days.

4.2 Median Analysis

Beginning with the winter of 2007-2008, each ski season within the range of study is subject to median analysis via a permutation testing method. The median analysis establishes the presence of significant differences between traffic counts on weekdays versus weekends, weekdays with snow events versus weekdays without snow events, and weekend days with snow events versus weekend days without snow events.

Table 4.5
2011–2012 Median Cluster Measures Per Winter Variable

Cluster	No of Observations	Types of Days	Median Base Depth (in)	% of Days That Are Numbered Storm Events	Median Storm Depth (in)	Median Time Between Storm Event
1	77	Weekdays, few weekend days	31.0	10.4%	6.5	12.0
2	48	Saturdays, weekend days	28.0	25.0%	4.3	15.5
3	13	Saturdays, Sundays, no Tuesdays, Wednesdays, or Thursdays	38.0	30.8%	8.9	2.0
4	44	Weekdays	13.0	9.1%	4.3	8.0

4.2.1 2007–2008 Winter Season

During the hours of 6:00 am to 4:00 pm, weekends have a higher median hourly traffic count than weekdays, shown in Figure 4.17. The greatest median count difference occurs between 9:00 am and 10:00 am where weekends experience 176.5 more cars per hour than weekdays. Through the resampling method, it is determined that the difference in hourly counts is significant for the hours of 7:00 am to 3:00 pm ($p < 0.001$).

As is seen in Figure 4.18, hourly counts for up-canyon traffic are greater from the hours of 4:00 am to 5:00 pm on weekdays with a storm event. The greatest median count difference occurs between the hours of 9:00 am and 10:00 am where weekdays with snow events show 131 more cars traveling up the canyon during that period. Median differences in weekdays with snow versus weekdays without snow are significant for the hours of 3:00 am to 12:00 pm ($p < 0.05$); however, counts before 7:00 am may be

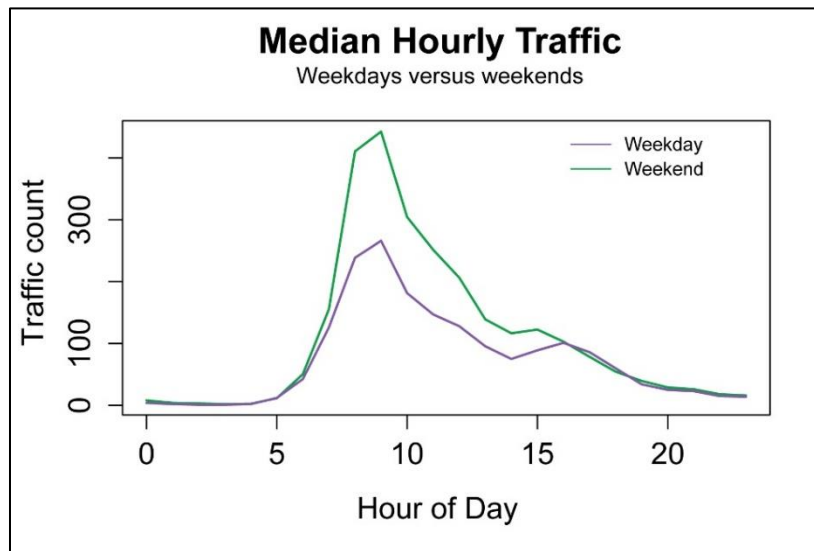


Figure 4.17 2007–2008 median hourly traffic comparison between weekdays and weekends.

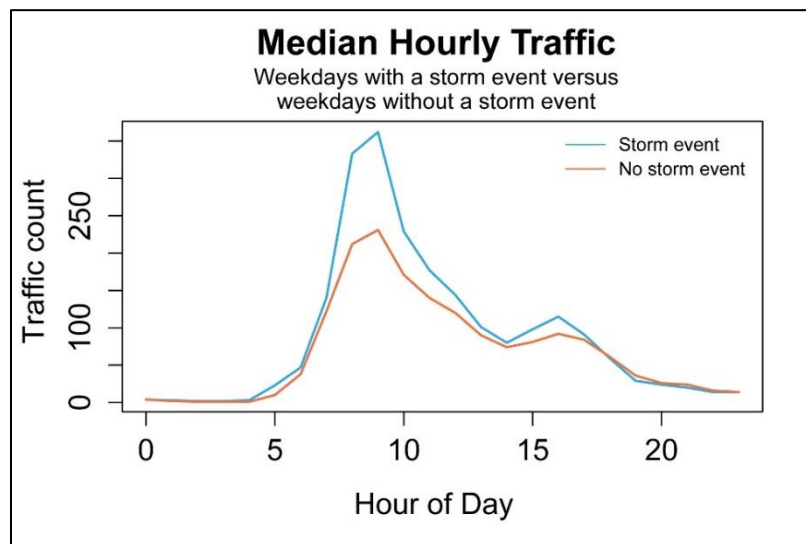


Figure 4.18 2007–2008 median hourly traffic comparison between weekdays with and without a storm event.

significant but not meaningful due to the small number of cars traveling up the canyon. Figure 4.19 illustrates that hourly car counts are greater from the hours of 7:00 am to 12:00 pm on weekend days with a snow event versus weekend days without a snow event. The greatest median count difference occurs between the hours of 8:00 am and 9:00 am where a weekend day with a storm experiences 299 more cars traveling up-canyon than a weekend day without a storm. Median differences of traffic counts on storm days versus nonstorm days are significant for the hours of 8:00 am to 10:00 am ($p < 0.05$).

4.2.2 2008–2009 Winter Season

Weekends have a higher median hourly traffic count than weekdays from the hours of 6:00 am to 4:00 pm, as can be seen in Figure 4.20. The greatest median count difference occurs between 9:00 am and 10:00 am where weekends experience 154 more

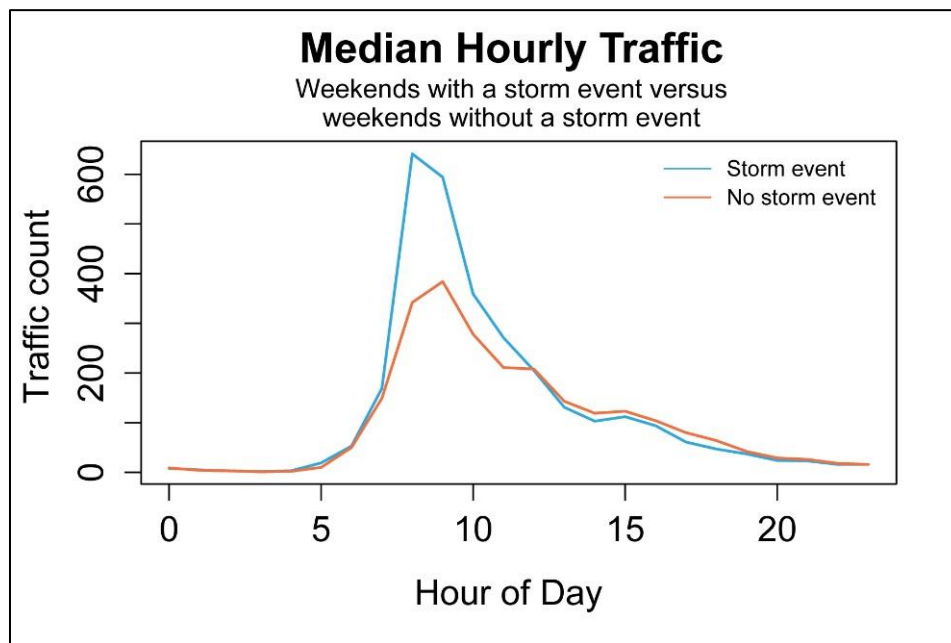


Figure 4.19 2007–2008 median hourly traffic comparison between weekend days with and without a storm event.

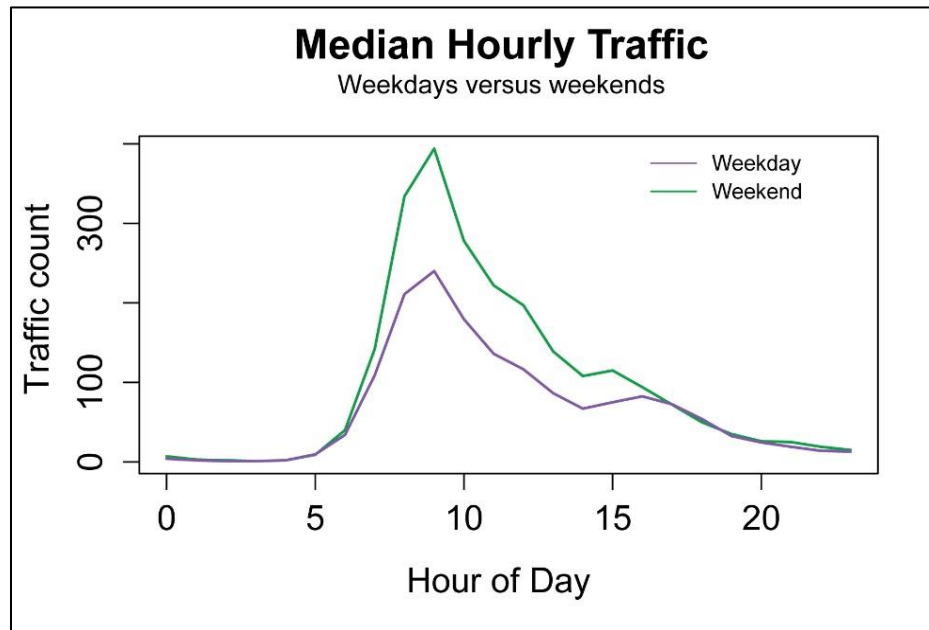


Figure 4.20 2008–2009 median hourly traffic comparison between weekdays and weekends.

cars per hour than weekdays. Through the resampling method, it is determined that the difference in hourly counts is significant for the hours of 6:00 am to 3:00 pm ($p < 0.001$).

Hourly counts for up-canyon traffic are greater from the hours of 4:00 am to 11:00 am on weekdays with a storm event, displayed in Figure 4.21. The greatest median count difference occurs between the hours of 8:00 am and 9:00 am where weekdays with snow events show 81 more cars traveling up the canyon during that period. Median differences in weekdays with snow versus weekdays without snow are significant for the hours of 7:00 am to 10:00 am ($p < 0.1$); some counts before 7:00 am may be significant but are not meaningful, due to the small number of cars traveling up-canyon.

Hourly car counts are greater from the hours of 7:00 am to 12:00 pm on weekend days with a snow event versus weekend days without a snow event, as is shown in Figure 4.22. The greatest median count difference occurs between the hours of 9:00 am and

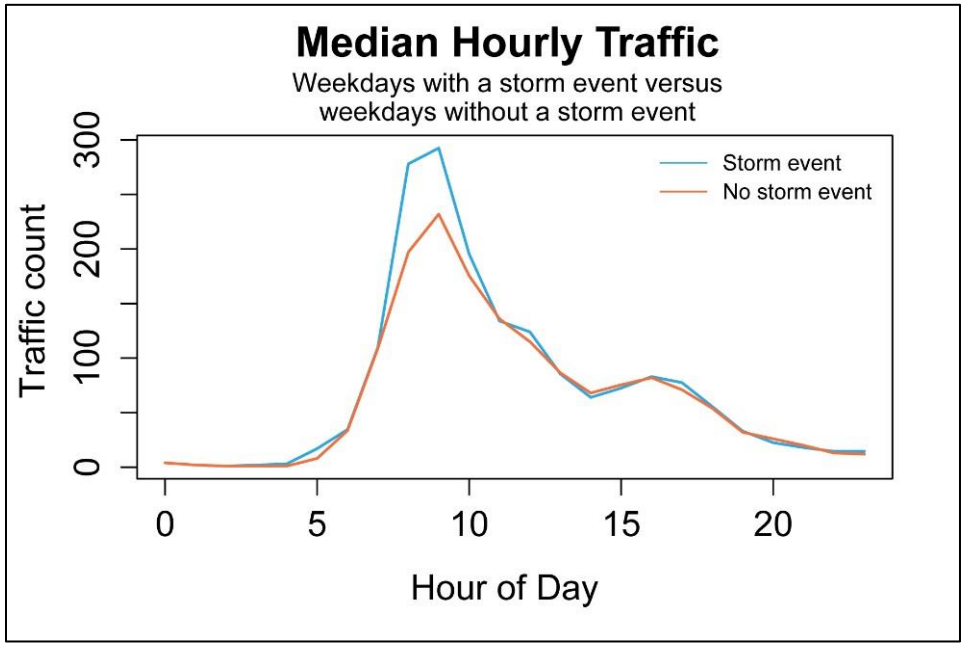


Figure 4.21 2008–2009 median hourly traffic comparison between weekdays with and without a storm event.

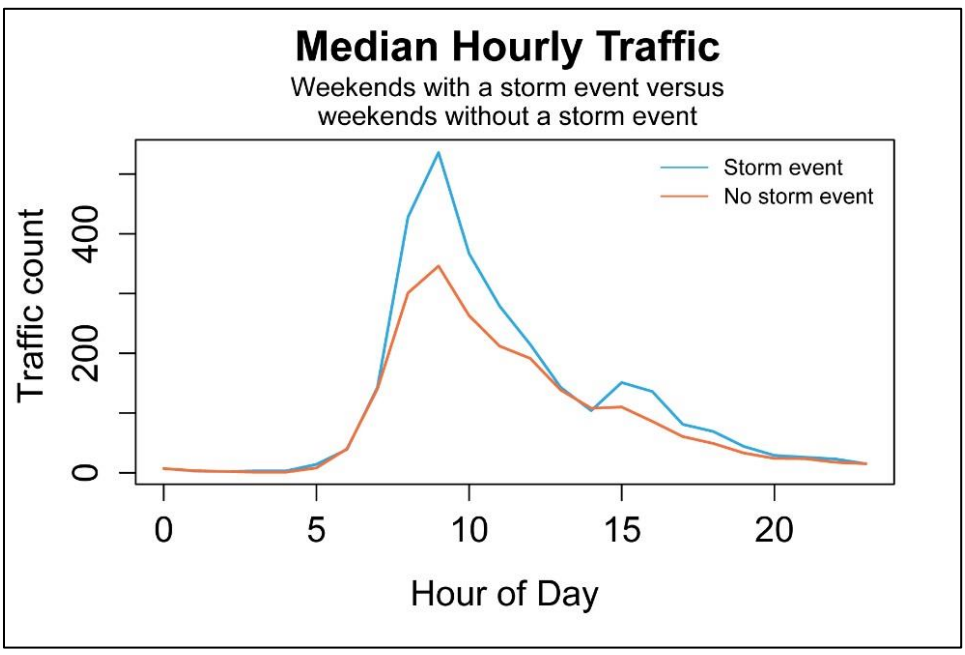


Figure 4.22 2008–2009 median hourly traffic comparison between weekend days with and without a storm event.

10:00 am where a weekend day with a storm experiences 190 more cars traveling up-canyon than a weekend day without a storm. Median differences of traffic counts on storm days versus nonstorm days are significant for the hours of 8:00 am to 11:00 am ($p < 0.1$).

4.2.3 2009–2010 Winter Season

Figure 4.23 shows that weekends have a higher median hourly traffic count than weekdays from the hours of 6:00 am to 4:00 pm. The greatest median count difference occurs between 9:00 am and 10:00 am where weekends experience 147.5 more cars per hour than weekdays. Through the resampling method, it is determined that the difference in hourly counts is significant for the hours of 6:00 am to 3:00 pm ($p < 0.001$).

Hourly counts for up-canyon traffic are greater from the hours of 4:00 am to 2:00 pm on weekdays with a storm event, as is shown in Figure 4.24. The greatest median

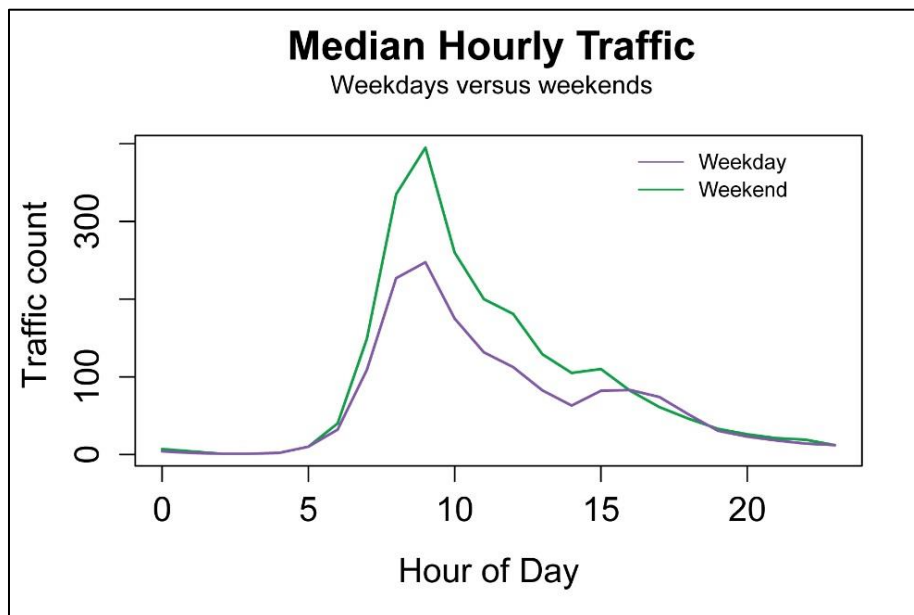


Figure 4.23 2009–2010 median hourly traffic comparison between weekdays and weekends.

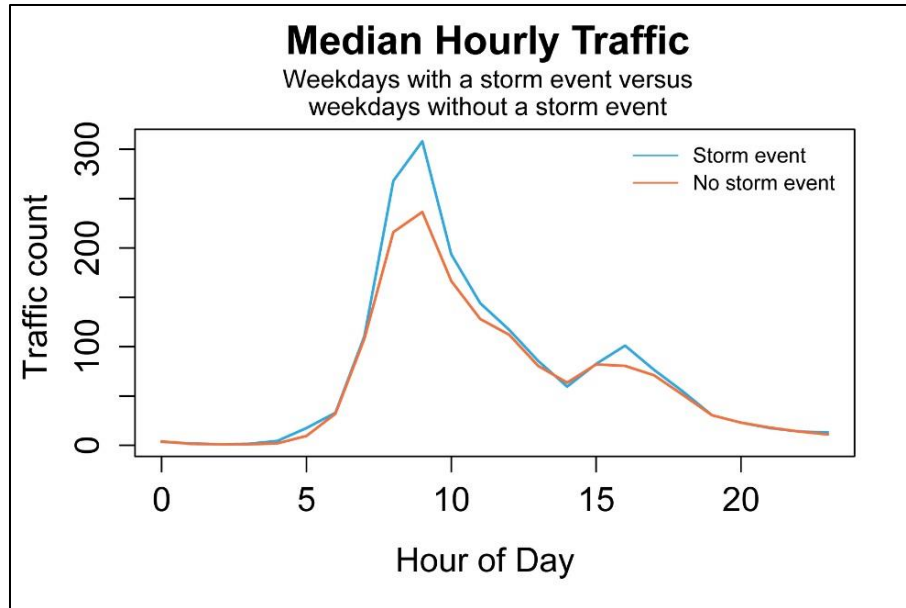


Figure 4.24 2009–2010 median hourly traffic comparison between weekdays with and without a storm event.

count difference occurs between the hours of 9:00 am and 10:00 am where weekdays with snow events show 71.5 more cars traveling up the canyon during that period.

Median differences in weekdays with snow versus weekdays without snow are significant for the hours of 8:00 am to 10:00 am, and at 4:00 pm ($p < 0.1$); some counts before 7:00 am may be significant but are not meaningful, due to the small number of cars traveling up-canyon.

Hourly car counts are greater from the hours of 5:00 am to 3:00 pm on weekend days with a snow event versus weekend days without a snow event, illustrated in Figure 4.25. The greatest median count difference occurs between the hours of 8:00 am and 9:00 am where a weekend day with a storm experiences 237.5 more cars traveling up-canyon than a weekend day without a storm. Median differences of traffic counts on storm days versus nonstorm days are significant for the hours of 7:00 am to 9:00 am, and 4:00 pm to 5:00 pm ($p < 0.05$).

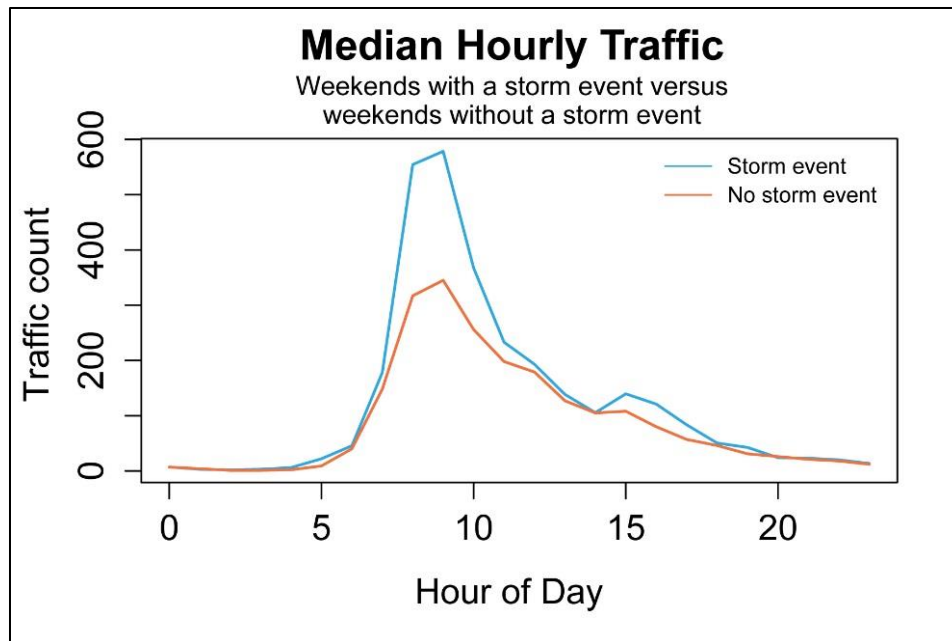


Figure 4.25 2009–2010 median hourly traffic comparison between weekend days with and without a storm event.

4.2.4 2010–2011 Winter Season

Weekends have a higher median hourly traffic count than weekdays from the hours of 6:00 am to 4:00 pm, supported in Figure 4.26. The greatest median count difference occurs between 9:00 am and 10:00 am where weekends experience 177.5 more cars per hour than weekdays. Through the resampling method, it is determined that the difference in hourly counts is significant for the hours of 7:00 am to 3:00 pm ($p < 0.001$).

Hourly counts for up-canyon traffic are almost identical between weekdays with a storm event and weekdays without a storm event, except for afternoon counts between 4:00 pm and 6:00 pm during which nonstorm days experience greater up-canyon traffic. Figure 4.27 indicates that the greatest median count difference occurs between the hours of 4:00 pm and 5:00 pm where weekdays without snow events show 37.5 more cars traveling up the canyon during that period. Median differences in weekdays with snow

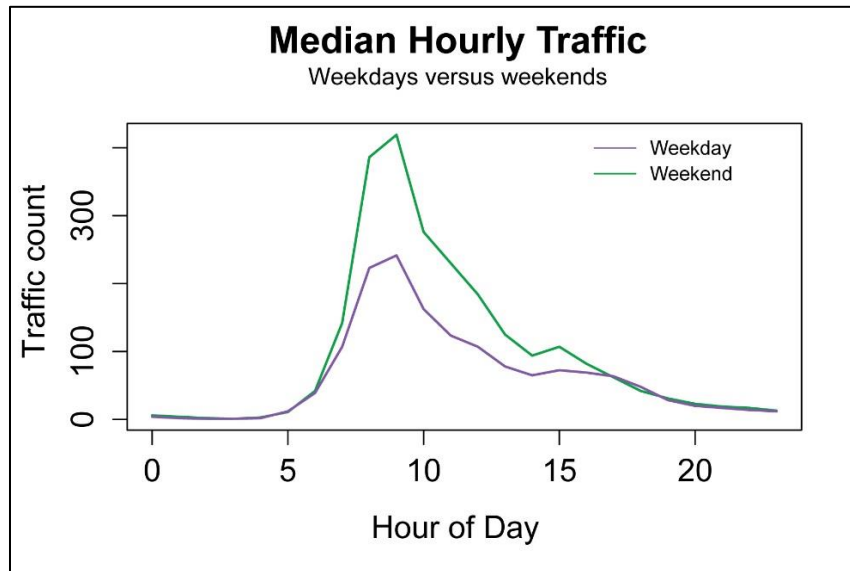


Figure 4.26 2010–2011 median hourly traffic comparison between weekdays and weekends.

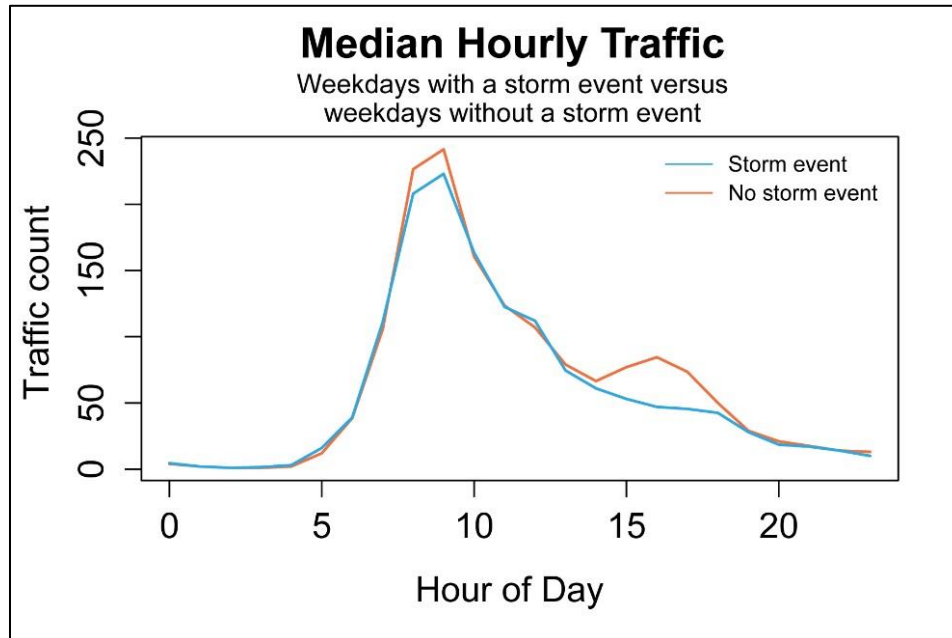


Figure 4.27 2010–2011 median hourly traffic comparison between weekdays with and without a storm event.

versus weekdays without snow are not significant ($\alpha=0.1$).

Hourly car counts are almost identical between weekend days with a snow event versus weekend days without a snow event, displayed in Figure 4.28. The greatest median count difference occurs between the hours of 8:00 am and 9:00 am where a weekend day with a storm experiences 43.5 more cars traveling up-canyon than a weekend day without a storm. Median differences in weekdays with snow versus weekdays without snow are not significant ($\alpha=0.1$).

4.2.5 2011–2012 Winter Season

During the hours of 6:00 am to 4:00 pm, weekends have a higher median hourly traffic count than weekdays, displayed in Figure 4.29. The greatest median count difference occurs between 8:00 am and 9:00 am where weekends experience 126 more cars per hour than weekdays. Through the resampling method, it is determined that the

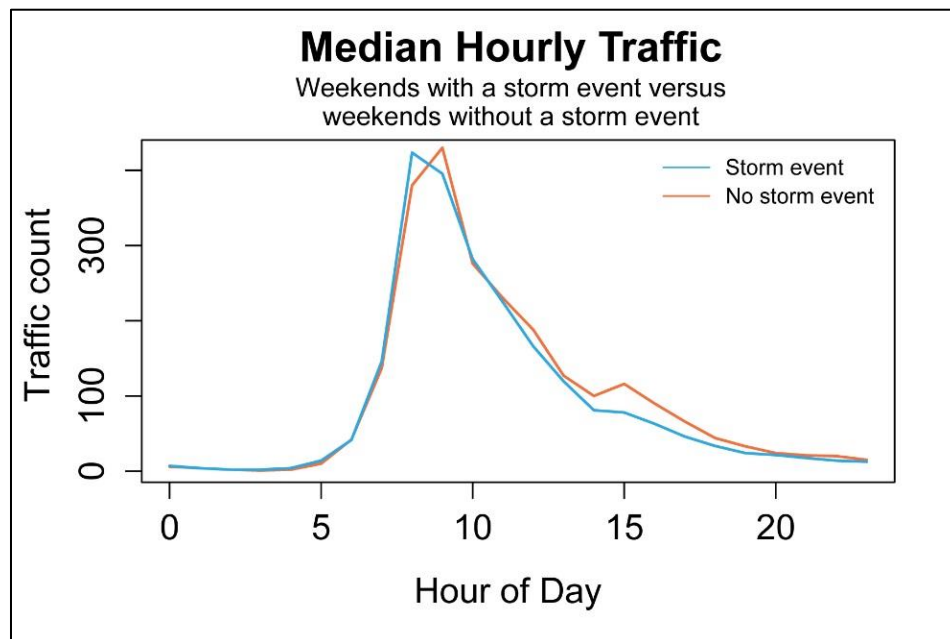


Figure 4.28 2010–2011 median hourly traffic comparison between weekend days with and without a storm event.

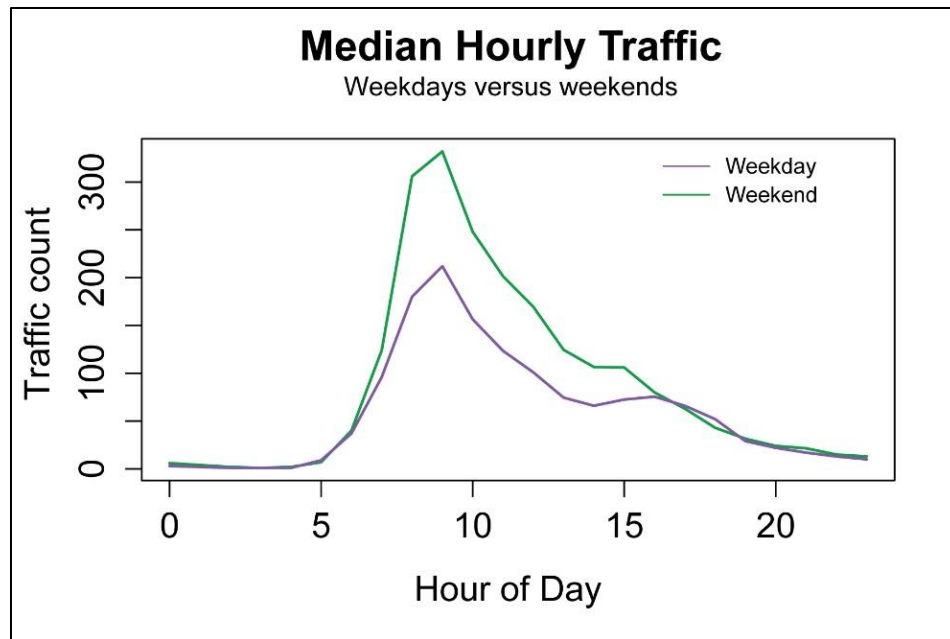


Figure 4.29 2011–2012 median hourly traffic comparison between weekdays and weekends.

difference in hourly counts is significant for the hours of 7:00 am to 3:00 pm ($p < 0.001$).

Hourly counts for up-canyon traffic are greater from the hours of 4:00 am to 11:00 am on weekdays with a storm event, as shown in Figure 4.30. The greatest median count difference occurs between the hours of 8:00 am and 9:00 am where weekdays with snow events show 149 more cars traveling up the canyon during that period. Median differences in weekdays with snow versus weekdays without snow are significant for the hours of 4:00 am to 9:00 am ($p < 0.05$); however, counts before 7:00 am may be significant but are not meaningful, due to the small number of cars traveling up canyon.

Hourly car counts are almost identical between weekend days with a snow event versus weekend days without a snow event, as shown in Figure 4.31. The greatest median count difference occurs between the hours of 8:00 am and 9:00 am where a weekend day with a storm experiences 33 more cars traveling up-canyon than a weekend day without a

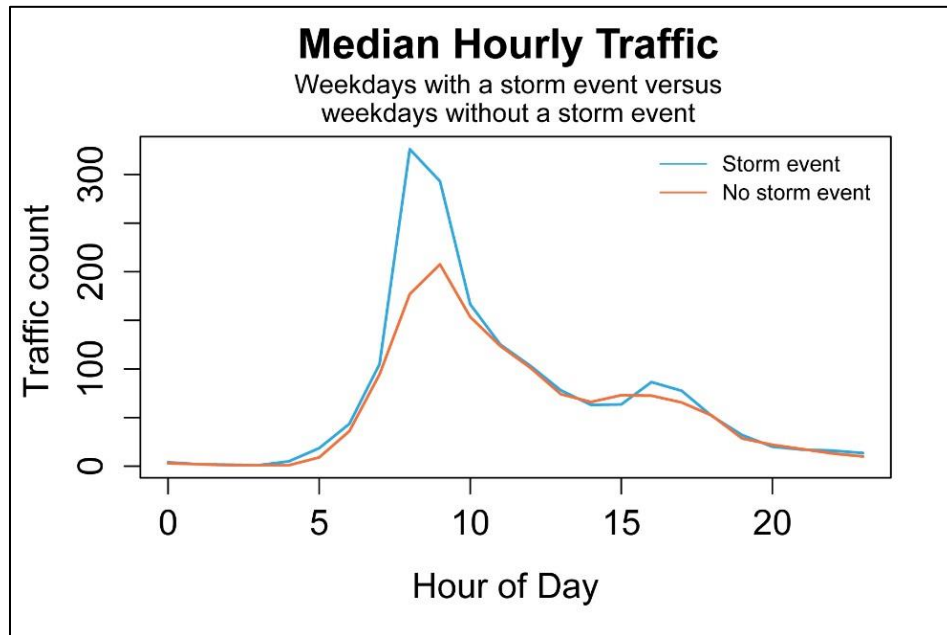


Figure 4.30 2011–2012 median hourly traffic comparison between weekdays with and without a storm event.

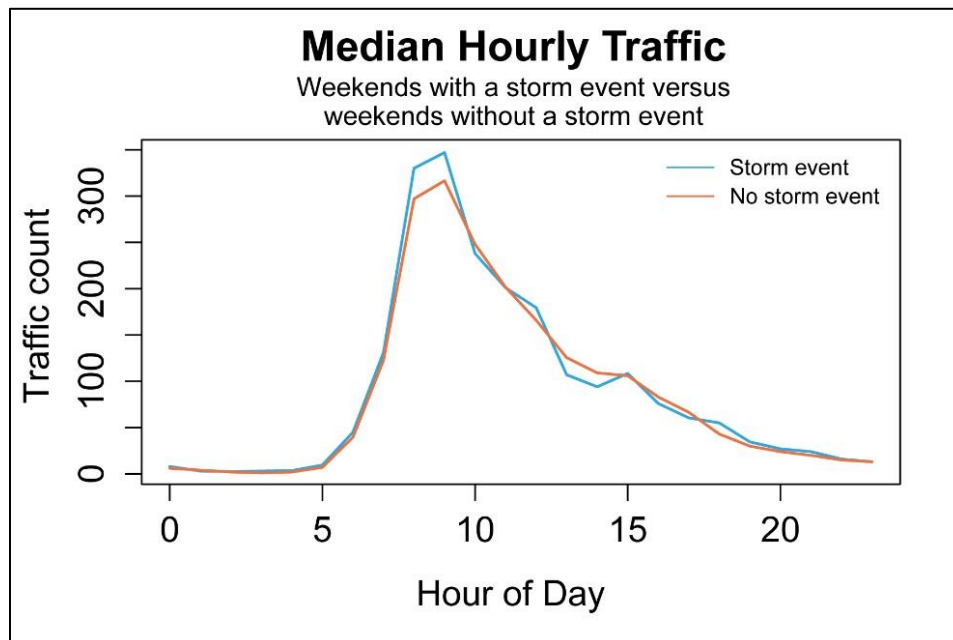


Figure 4.31 2011–2012 median hourly traffic comparison between weekend days with and without a storm event.

storm. Median differences in weekdays with snow versus weekdays without snow are not significant ($\alpha = 0.1$).

CHAPTER 5

DISCUSSION

5.1 Characteristics of Seasonal Clusters

Cluster prototypes follow a similar function, but have different amplitudes for vehicle counts. There is a strong indication that traffic data cluster according to day of week, but that clusters with similar distribution among days of week differ with respect to other seasonal variables represented in the dataset.

5.1.1 2007–2008 Winter Season

Cluster group 3 has the highest amplitude of traffic volume. The majority of observations within cluster group 3 fall on a Saturday, followed by Sunday. Given that weekend recreational travel is typically higher than recreational travel on weekdays, it is unsurprising that the highest traffic flows occur on a weekend day. The median base depth of days within cluster group 3 is 58.0” and is below the seasonal median of 65”, indicating that group 3 observations may occur towards the beginning and end of the season. However, group 3 has a high percentage of storm days as well as the smallest number of days since the previous storm event, suggesting that weekdays within the group elicit a higher traffic volume to resorts in response to storm events.

Cluster group 1 has the second-highest amplitude of which the majority of observations fall on a Sunday. Similar to group 3, it is not abnormal that traffic volumes

associated with a weekend day are greater than weekdays. The median base depth of group 2 is 53.0”, also indicating that group observations may occur towards the beginning or end of the season. Similar to group 3, cluster group 2 has a high percentage of storm days and the greatest median storm depth of all the cluster groups, indicating that traffic patterns of days within the cluster are a result not only of the day of week but also of the presence of storm events.

Cluster group 2 has the second-lowest vehicle counts within the season. The median base depth of observations within group 2 is 73.5” and is higher than the seasonal median. The proportion of storm days within the group is approximately the same as the proportion of seasonal storm days, and the median storm depth is not notably different from the other clusters. It is possible that storm days within the season tended to fall on weekend days and that traffic responses to storm events then occurred predominately on weekend days.

Cluster group 4 has the lowest vehicle counts within the season. The median base depth and percent of numbered storm events are well below that of the season, and the majority of observations falling within the group occur at the very beginning of November and at the end of April when resorts may not have been open.

5.1.2 2008–2009 Winter Season

Cluster group 5 has the highest vehicle counts. The bulk of observations fall on Saturdays, and no observations occur on Thursday or Friday. Again, higher traffic counts associated with weekend recreational travel are unsurprising. The median base depth is 43.5” and is just below that of the season as is the percentage of observations occurring during a numbered storm event. The median storm depth is the lowest of all the cluster

groups, and it can be inferred that the amplitude of the cluster group vehicle counts can generally be attributed to the day of week.

Cluster group 1 has the second-highest traffic volumes. The majority of observations fall on a Sunday, followed by Saturday. There is very little representation of weekdays within the cluster. The median base depth of the cluster is lower than that of the season, and the percentage of numbered storm events is just above the seasonal median. The median storm depth is the highest of all the cluster groups, signaling that traffic response may be in part a response to large storm events.

Cluster group 3 has the third-highest traffic volumes, and the majority of observations occur on Friday and Thursday. The median base depth of the cluster is above the seasonal median while the median time between storm events of the cluster is 0 days. Numbered storm events account for 47.0% of group observations, suggesting that higher traffic counts may occur on a Friday or a Thursday with the presence of a storm event, but that the influence of weekend days influences traffic volumes more than the presence of a storm event.

Cluster group 2 has the second-lowest vehicle counts. Observations are relatively uniform among weekdays Monday through Thursday. The median base depth within the group is the same as the seasonal median at 45", but at 18.0%, the number of observations coinciding with numbered storm events is lower than that of the season. The dispersion of numbered storm events indicates that storms typically occurred on weekend days, thus tempering the overall traffic responses to storms that may occur on a weekday.

Cluster group 4 has the lowest traffic volume and appears to capture observations

occurring at the beginning and end of the season with a median base depth of 11.0". The cluster also has the lowest proportion of numbered storm events; only 14.0% of observations within the group occur during a storm.

5.1.3 2009–2010 Winter Season

Cluster group 1 has the highest traffic volume. Observations falling on Saturdays dominate the cluster distribution followed by Sundays. There are no observations that occur on Tuesdays, Wednesdays, or Fridays. The median base depth of cluster group 1 is 50.5" and is greater than the seasonal median. The median storm depth is just above the seasonal median, but the percentage of observed storm events is far above the seasonal median, measured at 41.7%. Observations occurring on Mondays or Thursday within the cluster coincide with large storm events, supporting the hypothesis that significant snow events impact up-canyon traffic volumes.

Cluster group 2 has the second-highest vehicles counts. Observations overwhelmingly occur on Sundays and Saturdays, notably followed by Fridays and Wednesdays. The median base depth of cluster observations is 49.0" and the median storm depth is 12.6". Median number of days since the previous storm event is 7; however, at 18.9%, the proportion of days that are numbered storm events within cluster group 2 is not significantly higher than the seasonal median. The presence of weekdays in this cluster support the hypothesis that, while weekend day still has the greatest influence on traffic volumes, the occurrence of a major storm after a prolonged dry spell does impact vehicle counts traveling up-canyon.

Cluster group 4 has the second-lowest traffic volumes and is comprised mostly of weekday observations. Median base depth and time since the previous storm are

identical to group 2, with only a slightly lower proportion of numbered storm events. The median storm depth of the cluster is 7.1". Given the occasional occurrence of weekday observations in Cluster groups 1 and 2, Cluster group 4 suggests that amplified weekday traffic response to storm events follow high rates of 24-hour storm accumulation and smaller storms may not elicit the same increase in weekday volumes.

Cluster group 3 has the lowest traffic volumes, and is composed mostly of weekdays. A median base depth of 7.0" indicates that cluster observations trend towards the beginning and end of the winter season.

5.1.4 2010–2011 Winter Season

The 2010-2011 winter season is notable in that there was an abnormally high seasonal snowfall, and that numbered storm events seemed to have a greater number of days with small accumulation totals but that were considered to be part of a longer, numbered storm event.

Cluster group 1 has the highest traffic volume. The majority of observations occur on Saturdays around which observations are distributed normally. All days of the week have at least one observation except for Wednesday, which has none. At 56.5", the median base depth of the group is nearly identical to the seasonal median. The percentage of numbered storm events within the group is also nearly identical to the seasonal median, comprising 33.3% of observations within the cluster. The median storm depth of group observations is measured at 9.8" and is greater than that of the season. Days since the previous storm is also identical to the season as a whole with a median of 3.0 days between storm events. This cluster group further supports the hypothesis that weekday vehicle counts may increase and have similar amplitudes to those of a weekend day with

the presence of a storm event featuring high accumulation.

Cluster group 4 has the second-highest counts. Observations occur predominately on Sunday followed by Saturday, but observations are also uniformly distributed among the weekdays. The median base depth of days within the group is 58.0” and has a median storm depth above that of the season at 8.6”. Median number of days since the previous storm is calculated to be 5 and is above the seasonal median. Cluster group 4 has the greatest percentage of numbered storm events at 40.0% of group observations. Similar to group 1, the presence of weekday observations reaching weekend traffic amplitudes would support the claim that major storm events will result in higher than normal vehicle counts.

Cluster group 2 has the second-lowest traffic volumes. Observations occur mostly on weekdays with a small peak on Friday. The median base depth of the group is 58.5” and is higher than the seasonal median; however, the proportion of numbered storm events and the median storm depth are both lower than the seasonal median. It is likely that weekdays with a numbered storm event and storms with higher accumulation rates clustered into group 1 or 4, and would explain a lower proportion of storms and smaller storm totals within the group.

Cluster group 3 has the lowest traffic volumes. Observations occur predominately on weekdays. A median storm depth of 40.5 indicates that group 3 values trend towards the beginning of the season. A small median storm depth of 3.7” would not be expected to increase traffic volumes.

5.1.5 2011–2012 Winter Season

The 2011-2012 winter season is notable in that there was abnormally low seasonal snowfall, and that there were unusually long periods between storm events. Cluster group 3 has the highest measured traffic volumes. Almost all observations occur on Sundays or Saturdays, with only one observation on both Friday and Monday and no observations on Tuesday, Wednesday, or Thursday. The median base depth is 38.0” and is greater than the seasonal median of 24.5”. At 30.8% of observations, percent of numbered storm events is twice the seasonal median. Median storm depth within the group is 8.9” and is also greater than the seasonal median of 5.5”. Observations within this group support the hypothesis that weekends will experience higher recreational traffic volumes than weekdays.

Cluster group 2 has the second-highest hourly traffic flows. Observations are normally distributed around Saturday. The median base depth is just above that of the season, measured at 28.0”, and the median storm depth is 4.3”. While the median storm depth is just under the seasonal median, the percent of storm days within the group represent 25.0% of the total number of observations within the group. Cluster group 2 also has the highest median time between storm events, calculated at 15.5 days.

Considering the seasonal variables, the substantial number of weekdays within the cluster group supports the hypothesis that seasons with infrequent storm events are likely to have increases in resulting canyon traffic regardless of the day of week. Other study seasons that have stronger regularity of storm events typically show that clusters with the highest amplitudes are strongly associated with weekend days. The considerable number of weekday observations within this cluster suggest a shift in traffic responses during an

irregular snow year to be more responsive to prolonged periods without a storm event.

Cluster group 1 has the second-lowest vehicle counts. Observations are normally distributed around Wednesday. The median base depth of the cluster is 31.0”, but snow events compose only 10.4% of group observations.

Cluster group 4 has the lowest measured traffic volumes. Observations occur predominately on weekdays with few weekend observations. The median base depth of the group is 13.0”, suggesting that observations in the cluster typically occur toward the beginning or the end of the season.

5.2 Testing Significance Between Day of Week and Presence of Storm

It is hypothesized that weekends experience higher traffic counts than weekdays. The resampling method used to compare weekdays to weekends shows a significant difference between weekday counts and weekend counts for all seasons of study. This is unsurprising given previously referenced studies whose findings display significant differences between traffic on workdays versus nonworking days. Workdays are thus shown, regardless of storm event, to have lower up-canyon traffic flows than weekends for all seasons included in this research.

What is of particular interest, and what the original research goals seek to address, are any responses of traffic demand in Big Cottonwood Canyon to storm events. The primary objective is to examine hourly demand response to storm events using up-canyon traffic counts and to quantify any significant changes in traffic counts relating to storm events. It was expected at the outset of this research that days with snow events would display higher vehicle counts than days without snow events, particularly during morning

traffic flows. Given that weekend traffic patterns differ from weekday traffic patterns, the data must be grouped into subsets that allow for comparison of weekdays with snow events to weekdays without snow events, and weekends with snow events to weekends without snow events.

Comparison of weekdays with storm events to weekdays without storm events of the 2007-2008 season substantiate research hypotheses that snow events will have a positive impact on up-canyon vehicle counts. Significant differences in median hourly traffic counts are found between the hours of 3:00 am to 12:00 pm. While significant median differences in the early morning traffic counts do exist, they are not necessary meaningful given the small number of vehicles traveling up-canyon at that hour. The greatest difference in median hourly vehicle counts occurs between 9:00 am and 10:00 am. One explanation for the observed hour of peak difference may be that some local skiers are able to modify their work schedule to allow for morning skiing on storm days.

Median analysis of storm and nonstorm weekend vehicle counts during the 2007-2008 season also supports research hypotheses that storm days will have higher hourly traffic volumes than nonstorm days. Significant differences in count medians only last through 10:00 am. One explanation for this is that weekends experience a higher number of visiting skiers who will travel to the resort regardless of a snow event, and that the presence of a weekend storm will influence when people decide to travel to resorts in BCC.

Study results show that for the most part, days with snow events do have significantly higher morning traffic counts than those without. Significance testing of the 2010-2011 season yielded some surprising results. A plot of the distribution of median

hourly traffic counts on weekdays without a storm event compared to weekdays with a storm event show marginally higher hourly counts on days without a storm. Median hourly distributions comparing weekend days without storm events to weekend days with storm events show that hourly traffic volumes are almost identical between the two. There was no significant difference between vehicle counts during snow events and nonsnow events of either weekdays or weekends. This is quite different than the other seasons within the study, some of which show up to 300 more cars per hour on days with storm events. The 2010-2011 season had a record-breaking snow year in much of the western region of the country, and is a likely factor of this atypical behavior.

CHAPTER 6

CONCLUSION

There has been significant growth in research over the past decade aimed at addressing potential impacts of seasonal climate variables on recreational user demand at ski resorts. This has been predominately in response to mounting evidence that climate change is likely to alter normal characteristics of winter seasons in mountainous regions, thus impacting viability of ski resorts. Research in the field has focused primarily on empirical measures of visitation response during poor snow years; however, no known studies have addressed how fluctuations in seasonal variables might influence daily traffic demand, hourly vehicle volumes, and network congestion to ski resorts. This study provides preliminary insight on winter traffic patterns in Big Cottonwood Canyon as they relate to seasonal climate variables of storm frequency and depth.

Research of seasonal traffic should be further examined using a more robust methodology that allows for seasonal variables to be considered together when assessing potential responses in traffic to ski resorts in Big Cottonwood Canyon. Continuing to assess climate factors and their combined impact on traffic demand in BCC will expand the capacity to forecast and manage canyon traffic demand of future winter seasons. Such research would be suitable to inform demand-based forecasting and storm-responsive expansions in park-and-ride transit service in Big Cottonwood Canyon.

REFERENCES

- Abatzoglou, J. (2011). Influence of the PNA on declining mountain snowpack in the western United States. *International Journal of Climatology*, *31*, 1135–1142.
- Alvarez, P., Hadi, M., & Zhan, C. (2010). Data archives of intelligent transportation systems used to support traffic simulation. *Transportation Research Record*, *2161*, 20–28.
- Anderberg, M. R. (1973). *Cluster analysis for applications*. New York: Academic Press.
- Bales, R. C., Molotch, N. P., Painter, T. H., Dettinger, M. D., Rice, R., & Dozier, J. (2006). Mountain hydrology of the western United States. *Water Resources Research*, *42*(8), 1–13.
- Breiling, M., & Charamza, P. (1999). The impact of global warming on winter tourism and skiing: A regionalised model for Austrian snow conditions. *Regional Environmental Change*, *1*, 4–14.
- Burki, R., Elsasser, H., & Abegg, B. (April 9–11, 2003). Climate change—Impacts on the tourism industry in mountain areas. Proceedings from ICCCT '03: *The First International Conference on Climate Change and Tourism*. Djerba, Tunisia.
- Changnon, S., & Changnon, D. (2005). Lessons from the unusual impacts of an abnormal winter in the USA. *Meteorological Application*, *12*, 187–191.
- Chung, E. (2003). Classification of traffic pattern. Proceedings from ITS '03: *The 10th ITS World Congress*. Madrid, Spain.
- Efron, B. (1979). Bootstrap methods: Another look at the jackknife. *Annals of Statistics*, *7*, 1–26.
- Elsasser, H., & Messerli, P. (2001). The vulnerability of the snow industry in the Swiss Alps. *Mountain Research and Development*, *21*, 335–339.
- Federal Highway Administration. (2001). *Traffic monitoring guide*. Washington, DC: U.S. Government Printing Office.
- Galloway, R. W. (1988). The potential impact of climate changes on Australian ski fields. In G. I. Pearman (Ed.), *Greenhouse: Planning for climate change* (pp. 428–437). Melbourne, Australia: CSIRO/Brill.

- Gilbert, D., & Hudson, S. (2000). Tourism demand constraints—A skiing participation. *Annals of Tourism Research*, 27, 906–925.
- Governor's Office of Planning and Budget. (2006). *Utah ski database*. Salt Lake City, UT: Governor's Office of Planning and Budget.
- Harrison, R., Kinnaird, V., McBoyle, G., Quinlan, C., & Wall, G. (1986). Climate change and downhill skiing in Ontario. *Ontario Geographer*, 28, 51–68.
- Jones, L. P. (2010). *Assessing the sensitivity of Wasatch snowfall to temperature variations* (Unpublished master of science thesis). University of Utah, Salt Lake City, Utah.
- Kaufman, L., & Rousseeuw, P. J. (1990). *Finding groups in data: An introduction to cluster analysis*. Hoboken, NJ: John Wiley & Sons.
- Knowles, N., Dettinger, M., & Cayan, D. (2007). *Trends in Snowfall Versus Rainfall for the Western United States, 1949-2001. Prepared for California Energy Commission Public Interest Energy Research Program*. Project Report CEC-500-2007-032.
- Koenig, U., & Abegg, B. (1997). Impacts of climate change on winter tourism in the Swiss Alps. *Journal of Sustainable Tourism*, 5, 46–58.
- Lee, J. (2011, February 21). Big holiday crowds challenge some Utah ski resorts. *Deseret News*. Retrieved from <http://www.deseretnews.com/article/705367179/Big-holiday-crowds-challenge-some-Utah-ski-resorts.html>
- McBoyle, G., & Wall, G. (1987). The impact of CO₂-induced warming on downhill skiing in the Laurentians. *Cahiers de géographie du Québec*, 31(82), 39–50.
- Minder, J. R. (2010). The sensitivity of mountain snowpack accumulation to climate warming. *Journal of Climate*, 23, 2634–2650.
- Moen, J., & Fredman, P. (2007a). Climate change and downhill skiing in Sweden. *Journal of Sustainable Tourism*, 15, 418–437.
- Moen, J., & Fredman, P. (2007b). Effects of climate change on alpine skiing in Sweden. *Journal of Sustainable Tourism*, 15, 418–437.
- Mote, P. W., Hamlet, A. F., Clark, M. P., & Lettenmaier, D. P. (2005). Declining mountain snowpack in western North America. *American Meteorological Society*, 86, 39–49.
- National Ski Areas Association. (2011). *Kottke national end of season survey 2010/2011*. Lakewood, CO: Author.
- Null, S. E., Viers, J. H., & Mount, J. F. (2010). Hydrologic response and watershed

- sensitivity to climate warming in California's Sierra Nevada. *PLoS ONE*, 5, e9932.
- Pachauri, R. K. (2007). *Climate Change 2007: Synthesis Report*. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Vol. 446): IPCC.
- Pickering, C. M., Castley, J. G., & Burt, M. (2010). Skiing less often in a warmer world: Attitudes of tourists to climate change in an Australian ski resort. *Geographical Research*, 48, 137–147.
- Scott, D., & Becken, S. (2010). Adapting to climate change and climate policy: Progress, problems and potentials. *Journal of Sustainable Tourism*, 18, 283–295.
- Scott, D., Dawson, J., & Jones, B. (2008). Climate change vulnerability of the US Northeast winter recreation-tourism sector. *Mitigation Adaptation Strategies for Global Change*, 13, 577–596.
- Scott, D., & Lemieux, C. (2010). Weather and climate information for tourists. *Procedia Environmental Sciences*, 1, 146–183.
- Scott, D., & McBoyle, G. (2007). Climate change adaptation in the ski industry. *Mitigation Adaptation Strategies for Global Change*, 12, 1411.
- Scott, D., McBoyle, G., Minogue, A., & Mills, B. (2006). Climate change and the sustainability of ski-based tourism in eastern North America: A reassessment. *Journal of Sustainable Tourism*, 14, 376–398.
- Shih, C., Nicholls, S., & Holecek, D. F. (2008). Impact of weather on downhill ski lift ticket sales. *Journal of Travel Research*, 47, 359–372.
- Soriguera, F. (2012). Deriving traffic flow patterns from historical data. *Journal of Transportation Engineering*, 138, 1430–1441.
- Team, R. C. (2013). R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. Retrieved from <http://www.R-project.org>
- Thompson, B. (1993). The use of statistical significance tests in research: Bootstrap and other alternatives. *Journal of Experimental Education*, 61, 361–377.
- Unbehaun, W., Probstl, U., & Haider, W. (2008). Trends in winter sport tourism: Challenges for the future. *Tourism Review*, 63, 36–47.
- Utah Department of Transportation. (2006). *Little Cottonwood Canyon SR-210 Transportation Study*. Retrieved from http://wfrc.org/Previous_Studies/
- Vivian, K.-A. (2011). *Behavioural adaptation of skiers and snowboarders in the US*

- Northeast to climate variability and change* (Unpublished master of science thesis). University of Waterloo, Waterloo, Ontario.
- Ward, J. (1963). Hierarchical grouping to optimize and objective function. *Journal of the American Statistical Association*, 58, 236–244.
- Weijermars, W., & van Berkum, E. (2005). Analyzing highway flow patterns using cluster analysis. Proceedings from IEEE '05: *The 8th International IEEE Conference on Intelligent Transportation Systems*. Vienna, Austria.
- Wikstrom Economic & Planning Consultants. (2008). *Utah Skier/Snowboarder Survey 2007/2008*. Retrieved from <https://governor.utah.gov/DEA/Publications/07OtherPublications/>
- Wild, D. (1997). Short-term forecasting based on a transformation and classification of traffic volume time series. *International Journal of Forecasting*, 13, 63–72.
- Williams, B. M., & Hoel, L. A. (2003). Modeling and forecasting vehicular traffic flow as a seasonal ARIMA process: Theoretical basis. *Journal of Transportation Engineering*, 129, 664–672.