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The Impact of Adverse Weather on Freeway Bottleneck Performance

By

Joshua Lawrence Seeherman

A dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy

In

Engineering – Civil and Environmental Engineering

In the

GRADUATE DIVISION

Of The

UNIVERSITY OF CALIFORNIA, BERKELEY

Committee in Charge:

Professor Alexander Skabardonis, Chair
Professor Michael Anderson
Professor Michael Cassidy

Fall 2014

The Impact of Adverse Weather on Freeway Bottleneck Performance

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Abstract

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Joshua Lawrence Seeherman

Doctor of Philosophy in Engineering – Civil and Environmental Engineering

University of California, Berkeley

Professor Alexander Skabardonis, Chair

Congestion on freeways occurs when demand exceeds the available capacity. Common causes of recurring congestion, also known as freeway bottlenecks, include lane drops, on-ramp merges, and weaving sections. Adverse weather reduces traffic speeds and the maximum queue discharge flow at freeway bottlenecks. However, the impact of weather characteristics on bottleneck discharge flows has not been systematically investigated. This research investigated the relationship between bottleneck queue discharge flow and weather characteristics including rainfall intensity, wind speed, and visibility.

Queue discharge rates at four isolated merge bottlenecks within Orange County, California were measured utilizing an established methodology of cumulative count and occupancy curves. An analysis of how queue discharge varied by rainfall intensity revealed reduced discharge ranging from 5% in drizzle (rainfall <0.02 inches/hour) up to 27% in heavy rainfall (rainfall >0.1 inches/hour). However, variation in this single weather characteristic only accounted for a small percentage of the variability in discharge flow, particularly in light rain. Several hypotheses were proposed and tested utilizing the two additional variables of wind speed and visibility and dividing the periods of discharge flow into three groupings. Analyses based on these hypotheses better described the variation in queue discharge flow than the analysis with rainfall intensity alone. A model was developed to predict bottleneck discharge flow by combining data points from all sites. This model predicted that an increase in rainfall intensity of 0.1 inches per hour reduced queue discharge by approximately 1.8% at all sites after the onset of congestion.

This research shows that weather characteristics are an important predictor of bottleneck queue discharge rates. Forecasted weather patterns could be used to predict reductions in bottleneck capacity. Complementary research building on this work by examining changes in trip start time during adverse weather would allow an improved prediction of vehicle delay and travel time reliability. This information would allow traveler information services to incorporate weather characteristics in order to provide more accurate predicted route times for commuters.

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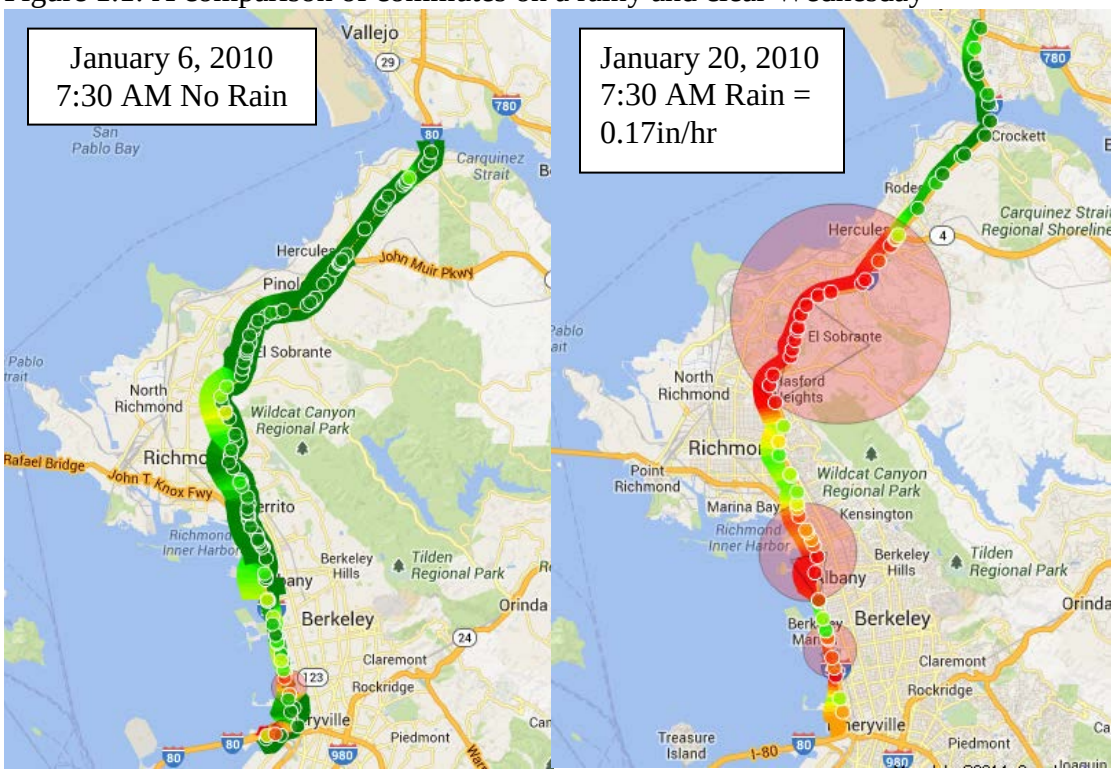
CHAPTER 1: INTRODUCTION

1.1 Motivation

It has long been understood anecdotally by motorists that adverse weather is likely to lengthen one's driving time, particularly during a commute in the peak hour. Micro effects of increased breaking distance caused by slippery roads, slower speeds and cautious drivers can combine to create reduced performance on the freeway. In locations of light volume, such as rural areas between cities, this can be a simple nuisance; in areas of congestion, particularly during the peak period, weather can create a commuting nightmare. Freeway bottlenecks, defined as points of recurring congestion where demand exceeds capacity forming a queue, are locations likely to have decreased discharge flow during weather resulting in increased travel times for daily commuters. For example, Figure 1.1 shows graphical representations of a daily morning commute on I-80 Westbound in California from the Carquinez Bridge to the Bay Bridge Toll Plaza. Both pictures were taken on Wednesday mornings, but the second was during a day where moderate rain was falling. Noting that darker colors (red) represent very slow speeds indicating congestion, there is a clear difference between the two. The small bottlenecks at the bottom of the picture have not only increased in size, but the largest change occurred when the series of small disturbances between SR 4 and Richmond coalesced into one multiple mile section of very heavy congestion.

Figure 1.1: A comparison of commutes on a rainy and clear Wednesday



Throughout the United States, bottlenecks are often so large and severe that they are referred to by name. Locally in the San Francisco Bay Area two examples of such

bottlenecks are the "MacArthur Maze" at the junction of I-80, 580, and 880 in Oakland and the "Novato Narrows" on US 101 in Marin County. These bottlenecks often define a commute and the ability to move through them controls overall trip time.

There has been extensive work on the general effects of weather on corridor characteristics such as speed and flow (Ibraham and Hall 1994, Kyte 2001) and some initial work describing discharge flow from an active bottleneck during weather (Dehman, 2012). However, all of these prior exercises only address weather with a discrete function, i.e. the effect of rain on speeds is aggregated into three categories of light, moderate, and heavy rain. None of these prior works have tried to explain the complexities of changes in discharge flow from an active bottleneck due to weather as a continuous function nor have they tried to address the variability in discharge flow. Additionally, unlike crashes, weather is not random and can be predicted up to five days in advance with ever-increasing accuracy. In the coming years, by inputting their route on a traveler information service such as 511.org drivers could see how weather might affect their commute for the entire week. In this manner, forecasting congestion due to weather is an arena worth exploring in greater detail. Additionally, as more emphasis is placed on managing freeway capacity as opposed to adding to it, understanding how bottleneck discharge flow changes during weather will be increasingly important for municipalities as they decide how to spend their improvement dollars.

1.2 Research Question and Contribution

For most major cities across the globe, rainfall can have a major effect on the performance of the transportation network. As these cities continue to mature the ability to expand capacity will decrease and the ability to understand how to manage traffic flow in a constrained space will be of ever increasing importance. This research will enhance knowledge on the ability to quantify the effect of adverse weather (e.g. rainfall intensity, wind speed, visibility) on the discharge flow from active freeway bottlenecks by examining the changes in discharge flow during different weather conditions. It is hopeful that the new findings will not only more accurately represent the relationship between weather effects and bottleneck performance with a continuous function but in addition will be generic across multiple bottlenecks which could lead to a more significant finding. Posed as a question, *can one generically describe the queue discharge flow of a freeway bottleneck under the influence of adverse weather?* While this dissertation only examines bottlenecks in Orange County, findings could be applied to bottlenecks in other areas which could be the first step for commute times to be predicted for different regions. There are many different metropolitan areas that have travel information systems already in place for performance inputs generated by this dissertation.

1.3 Dissertation Organization

The structure of this dissertation is broken up into three general sections with eight total chapters. The first section, comprising of Chapters 2 and 3, examines prior work by others and initial work examining the overall effects of weather on freeways here in California. Chapter 2 will show a literature review of prior outside research of the weather effects on freeway flow as well as methods of identifying freeway bottlenecks and factors that lead to congestion at freeway bottlenecks. It will be seen that while there is ample literature examining the effect of weather on basic freeway segments, there has been very little work on effect of the weather on the queue discharge rate of bottlenecks themselves, and all of the prior work has been discrete in nature, simply reporting the reduction in averages of light, medium and heavy rain but not addressing variability. Chapter 3 encompasses two sections of initial work that leads up to the main body of examination. In the first section, an attempt was made to isolate the effect of weather on vehicle delay on corridors in California and this showed that the contribution was significant in many different locations. Although this looked at corridor-wide vehicle delay, not bottleneck queue discharge, it established that for many corridors in California weather was a significant component of overall delay to drivers during their daily commutes. The second section of initial work focused on a specific local bottleneck in Pittsburg, California and found decreases in flows during five days of weather events.

In Chapters 4 and 5, the dissertation will move forward to exclusively examine queue discharge flow from an active bottleneck, including the data collection, methodology for both identifying the bottlenecks and mapping the weather data on to each period of congestion, presenting basic discrete findings and comparing those findings to prior work. In Chapter 4, the methodology of utilizing cumulative occupancy and count curves will be presented, and a subsequent list of four appropriate bottlenecks in Orange County, California that meet examination criteria will be shown. Weather data will be introduced and the procedure for mapping the different weather variables onto the periods of bottleneck congestion will be established. Chapter 5 will present basic discrete findings of reduction by light, medium, and heavy rainfall intensity and compare to prior work.

The final section constitutes the bulk of the analysis and seeks to understand the variability in the basic findings beyond the simple discrete bins. Chapter 6 will present five hypotheses starting with simple linear and quadratic regressions using the three different available weather variables of rainfall intensity, wind speed, and visibility, assuming all periods of discharge flow are independent. Two additional simple regressions using a fixed effects approach using no weather as a control will also be compared. The fifth hypothesis, referred to as the complex hypothesis, tries to incorporate prior weather conditions as well as performing a regression of differences between different periods of queue discharge. Chapter 7 will report the findings of these hypotheses; the complex hypothesis not only performed as well as the simple hypotheses but also generated more powerful generic findings. Chapter 8 will lastly include a recapitulation of the dissertation, discussion of limitations and suggestions for future work. There are many avenues that this work could be expanded upon, such as places with different intensities of weather and different driver behavior.

CHAPTER 2: LITERATURE REVIEW

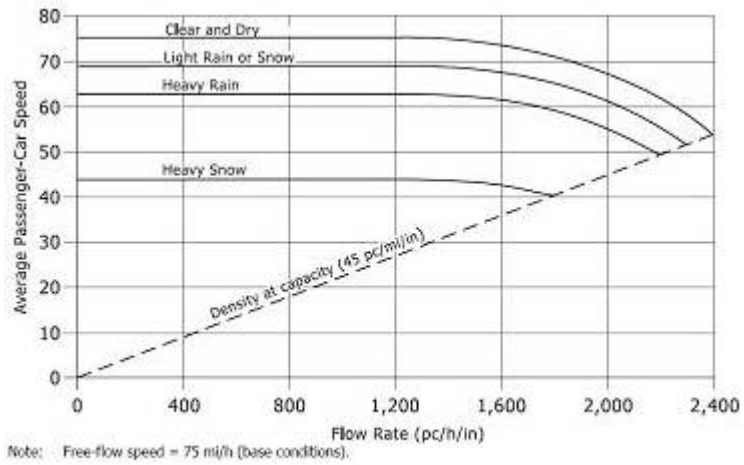
Although it has been well understood by motorists that adverse weather will affect ones commute, the study of this effect is a fairly small field within the area of congestion management. The literature review is divided into two sections which are as follows:

1) Effect of weather on basic freeway segments and bottlenecks
2) Identification of freeway bottlenecks

2.1 Effect of Weather on basic freeway segments and bottlenecks

The 2010 edition of the Highway Capacity Manual (HCM) follows previous editions and continues to address the effect of weather largely with one chart shown below in Figure 2.1. This approach has been criticized by many researchers as a simplistic view (Kyte 2001), and that critique has served as the rationale for a majority of the weather related traffic research in the past two decades.

Figure 2.1: HCM Adjustments by Weather Type



Conclusions drawn from Figure 2.1 are quite limited, as the curves are simplifications of complicated effects, particularly the curves for heavy rain and snow. Figure 2.1 was initially based upon the work of Ibrahim and Hall from Canada (1994) and Brilon and Ponzlet from Germany (1996). Ibrahim found a 10 to 20% reduction in maximum capacity with rain, with a range for reductions in speed from 2 kilometers per hour (kph) from light rain up to a 10 kph drop from heavy rain. Snow produced dramatic capacity decreases, with reductions ranging from 30% to 48%. Brilon expressed maximum capacity reduction in the context of vehicles per freeway lane, with rain creating a flow drop of 175 vehicles per hour per lane on a two-lane freeway (ph-pl), 150 on a three-lane. Darkness and rain resulted in a capacity drop that exceeded 250 vehicles per hour per lane.

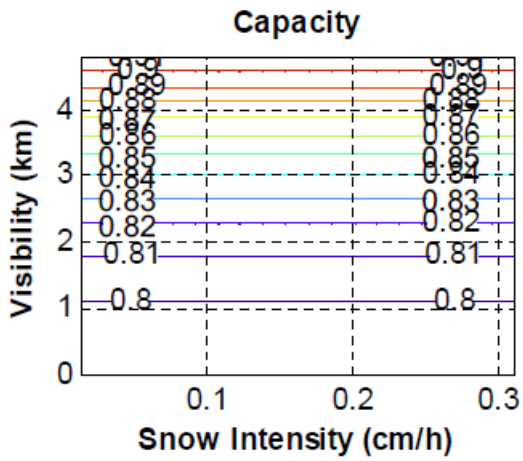
There have been a number of additional studies that sought to improve the understanding beyond the HCM, of which four will be mentioned. Kyte (2001) confirmed many of the Ibrahim and Hall values on rural Idaho freeways, utilizing instead the status of the

pavement (wet vs. dry) as opposed to precipitation type, and also noted speed reductions of 15% and 18% for high wind and fog, respectively. Kyte's results were only in relation to speeds and did not address capacity and flows as the study area was on rural roads. Saberi (2010) looked at three years of data on Interstate 5 in Portland, Oregon and found reductions similar to Kyte in the 95th percentile speed (10-20% reduction) as well as reductions in capacity. Reductions started at 0 to 110 vehicles ph-pl for drizzle slowly rising to 190 vehicles ph-pl during heavy rain. This was noted by Saberi as agreeing with the older study by Ibrahim and Hall. Saberi's study also noted that crash rates were higher after 3 hours of continuous rain, a common occurrence during the Portland rainy season. Smith (2004) found that the effect of rain on freeway operating speeds in urban Virginia was similar to the HCM, but that the HCM significantly underestimated capacity reduction.

Moving toward predictive papers that attempted to create a performance model, Byun (2010) developed an empirical model of rainy conditions on six New Jersey freeways. This was an attempt to move away from the previous narrative studies to provide an empirical model based on local driver behavior. Although the model does not address bottlenecks, it provided some insight as an early effort to show the importance of predicting travel times during weather events. The model estimated speed based on the existing traffic flow and rainfall intensity. Byun was able to verify his macroscopic model with data from other New Jersey freeways, but he did not analyze specific bottlenecks or areas of congestion.

A recent study reported by the FHWA (2006) and Rahka (2008) investigated rain and snow effects in Minneapolis, Seattle, and Baltimore and also additionally sought to create weather adjustment factors (WAF's) based upon multiple weather characteristics such as wind speed, precipitation intensity and visibility for both rainy and snowy weather. The findings confirmed the results reported by Ibrahim and Hall (1994) and produced a number of curves based upon the aforementioned characteristics. An example of a WAF for adjusting capacity for snowfall is shown below in Figure 2.2.

Figure 2.2: FHWA Sample Weather Adjustment Factors
for Capacity in Snowy Conditions
(multiply existing clear & dry capacity by factor in table)



One interesting additional finding by the FHWA work was that the speed drop during snow conditions for Baltimore drivers was less than for Minneapolis drivers, and the authors theorized perhaps that Minnesota drivers were more aware than Maryland drivers of the dangers of driving in adverse weather. This indicates that weather impacts can vary by location due to driver behavior. Rahka did not specifically identify bottleneck locations as sources of congestion or note the effect of weather on bottlenecks.

There are two prior works in the literature that have focused on the effect of weather on bottlenecks, albeit again at only the discrete level by aggregating flows into qualitative categories. Kim (2010) primarily examined characteristics of flow breakdown and congestion duration, as opposed to bottleneck discharge flow. She concluded that the duration of congestion did not change if the rain was prior to the onset of congestion but it did increase if rain occurred during the onset. Additionally, the drop from the maximum pre-breakdown discharge flow to post-breakdown queue discharge flow did not appear to change if rain occurred. However, many of the discharge flow quantities were quite low even without rain (1100-1900 vehicles/per hour/per lane), which might indicate a possible error in bottleneck identification, and does not address intensity of weather. The authors did not elaborate on where they measured the discharge, only that they used speed contour plots from the California Performance Measurement System (PeMS) for bottleneck identification. Dehman's work (2012) is much more of a stepping-stone to the work that will be conducted within this dissertation. He examined four urban sites in Milwaukee and created discrete correction values for discharge flow based on the severity of the weather. For example, light rain affected discharge flow between eleven and twelve percent depending on the site, while fog reduced discharge flow between four and seven percent.

Table 2.1 summarizes the literature review on the effect of weather on freeway corridors. The research within this dissertation will be a synergy between the works done on continuous effects of weather on basic freeway segments (Rahka and Byun) and those

that focused on bottlenecks but only produced discrete relationships (Kim and Dehman). This research will attempt to explore continuous relationships of weather but focus on the performance of active bottlenecks as opposed to simple freeway segments.

Table 2.1: Summary of Weather Effects on Roadway Parameters

Paper	*Location*	*Rain*	*Snow*
Ibrahim (1994)	*Toronto*	*10-20% capacity drop*	*30-50% capacity drop*
Brilon (1996)	*Germany*	*150-175 veh ph-pl capacity drop Up to 250 at night*	
Kyte (2001)	*Rural Idaho*	*Speed Reduction 9.5 km/h*	*Speed Reduction 16.4 km/h*
Smith (2004)	*Norfolk (VA)*	*10% drop in light rain, up to 30% in heavy rain*	
Rahka (2008)	*Multiple States*	*Light Rain 10-12% capacity drop*	*12-20% capacity drop*
Saberi (2010)	*Portland (OR)*	*0-190 veh ph-pl capacity drop*	
Byun (2010)	*New Jersey*	*I-80 average flow drop 365 veh ph-pl (25%)*	
Kim (2010)	*California*	*7.7 – 11.7% capacity drop*	
Dehman (2012)	*Milwaukee (WI)*	*10.9-13.4% capacity drop*	*9.9-10.7% capacity drop*

2.2 Identification of Bottlenecks

This dissertation examines queue discharge flow from an active bottleneck and by looking at the discharge as a continuous function it provides new insight into the causes of variability in discharge. While the literature review to this point has focused prior work looking at the effect of weather on freeways, one must also review the literature on factors involved in bottleneck creation and bottleneck identification. Without being able to properly identify a site as being an active bottleneck, it would be very difficult to conduct the analysis within this dissertation. An active freeway bottleneck is defined as a location where two requirements have been fulfilled: a queue has formed upstream, creating a situation where vehicles are discharging at a maximum rate, and that there are no downstream effects (such as queue spillover from a larger downstream bottleneck) that affect the ability to discharge at the maximum rate (Cassidy 1999). For example, sometimes the bottleneck of the toll booth at the entrance of San Francisco Bay Bridge can overwhelm smaller bottlenecks further upstream on the freeways that approach the toll booth itself.

Two important papers discussing queue discharge from an active bottleneck are Cassidy and Bertini (1999) and Agyemang-Duah and Hall (1991). The first paper discussed an initial drop in queue discharge at the onset of bottleneck congestion, followed by a recovery to a stable level but still lower than the free-flow capacity. Additionally, the researchers made use of a bottleneck identification technique using cumulative curves that will be the methodology utilized to perform the data collection within this dissertation. Agyemang-Duah and Hall further quantified this effect by citing a 6 to 30 minute transitional period to the reduced flow, and showed that on a freeway in Toronto due to a merging bottleneck flow was approximately 5 to 6 percent lower than capacity of a basic freeway lane. Chen (2004) built upon this with the help of detector data within California to identify bottlenecks through speed drops at detector stations. With the advent of the real-time database, Chen's methodology has enabled the California transportation agency (Caltrans) to identify bottlenecks in real time. Banks (2002) has also provided a summary of empirical freeway congestion research including a section on freeway bottlenecks.

Going further, there have also been research efforts to identify specific capacity changes of different types of bottlenecks. Sarvi (2007) examined merge bottlenecks due to on-ramps in Tokyo and found a capacity drop of approximately 7%. Furthermore, he noted that increases in volume in the median lane reduced lane changes and that the merge capacity was not related to the merge ratio.

A parallel effort to address human factors that cause the activation freeway bottlenecks has been documented by Joel Leisch in the ITE Geometric Design Handbook. Under Leisch's set of human factors, he cites the importance of recurring design elements particularly that all exit ramps are placed on the right side and that lanes will not be dropped by exit ramps. Once these basic expectations are removed, driver errors can occur which in turn lead to congestion and crashes. Unusual maneuvers, excessive task demands, and unexpected lane drops are a few of the human errors listed. Although not mentioned by Leisch, weather might create an "excessive task" for drivers causing congestion. Many causes of bottlenecks other than ramp junctions and weaves, such as solar glare, grade changes, sharp horizontal curves, and "exit only" lanes can lead to driver errors as drivers are faced with out of the ordinary geometry. However, the Leisch handbook fails to address weather, other than solar glare, as part of the guide on non-recurring bottlenecks. He states that non-recurring bottlenecks "cannot be addressed by the freeway designer, but rather are addressed by the freeway operator," suggesting the importance of crash response. This type of deficiency in showing how weather can affect different types of geometric bottlenecks is another example of why further research is needed on this topic. None of the papers mentioned above included weather as part of the analysis.

CHAPTER THREE: INITIAL WORK

As initial work for the main thesis, two investigations were undertaken to examine the effect of rainfall on freeways. The first investigation looked at quantifying weather delay as a portion of overall congestion on selected freeway corridors in California. Within this investigation, it was found that the rain was a significant effect on causing delay on many corridors, particularly those that typically have less daily congestion. The second section looked at a specific local bottleneck in Pittsburg, California and downstream flows on a small set of rainy days. Measuring the flow downstream from this bottleneck revealed considerable differences between rainy and clear days. The conclusions drawn from these two initial works strongly supported continuing further with research into bottleneck performance during adverse weather.

3.1 Weather Effects on Selected Freeway Corridors

The objective of the corridor-wide study was to examine a large number of locations statewide with varying weather and congestion (as prior work had only looked at a small number) to establish weather's contribution to delay on California freeways. Each location would consist of an approximately 10 mile stretch of freeway and the detectors contained within. This work analyzed an extensive set of historical traffic data from the state of California to gain a better understanding of the proportion of traffic delay that can be directly attributed to weather. A congestion estimation model was developed to estimate vehicle delays directly attributed to rain on 17 urban freeway corridors. It was found that delay due to rain ranged from 3% to 25% of the total delay, and the effects of weather vary significantly depending on both the type of weather and the amount of recurring delay on the freeway segment.

An additional intention of this study was to develop a procedure to calculate the weather related congestion delay from the overall congestion on California freeways and include it as a feature of the California Performance Measurement System (PeMS), extending the research conducted by Kwon (2005). PeMS collects and stores traffic data from over 30,000 loop detectors throughout California. The system produces several performance measures, and includes algorithms to identify bottlenecks and calculate the amount of traffic congestion delay by cause (i.e., excess demand, incidents and special events). The development of a procedure to calculate weather related congestion would significantly contribute to improved performance measurement on California freeways.

3.1.1 Approach and Data Collection

The approach for this section utilized the procedure encapsulated within *Measuring Recurrent and Non-Recurrent Congestion* by Skabardonis (2003) to analyze historical traffic data for seventeen freeway corridors from the PeMS database. The steps are as follows:

1. Utilizing the PeMS database, compile hourly flows and speeds for the study period for each detector within the selected corridor.

2. Calculate the length of a segment governed by each detector by finding the values of the mileposts halfway between each detector.
3. Calculate the vehicle miles traveled (VMT) on each segment by multiplying the flow from each detector by the segment length.
4. Calculate the vehicle-hours traveled (VHT) during the selected hour by dividing the VMT by the average speed taken from the detector.
5. Calculate the overall delay by finding the difference between VHT from Step 3 and VHT assuming a reference free-flow speed (60 mph).
6. Place delays into different categories, those occurring in dry, no-incident conditions (recurring) and those with incidents or weather.
7. Average these delays to create a mean value for recurring delay, non-recurring (incident) delay, and non-recurring (weather) delay.
8. Find the number of time periods that an incident or bad weather occurred. Divide this number by the total number of time periods to find a probability of weather or accidents occurring.
9. Utilize the following equation to calculate the average daily total delay,

Equation 1:

$$E(D) = E(D|O) + [E(D|I) - E(D|O)]*p(NR) + [E(D|W) - E(D|O)]*p(NR)$$

Where:
$E(D)$ = total delay, $E(D|O)$ = mean recurring delay,
$E(D|I)$ and $E(D|W)$ = mean non-recurring from incidents and weather,
$p(NR)$ = probability of non-recurring delay from incidents or weather.

10. Divide recurring delay by total delay to find the percentage caused by recurring congestion concerns.
11. Weight the remaining percentage by the probabilities of occurrence for the two types of non-recurring delay to find the percentage of the two types.

Weather data for this project were taken from two different sources depending on the location of the corridor. Whenever possible, rainfall was noted by examining the nearest National Weather Service (NWS) Remote Automated Weather Station ("RAWS"). Throughout the Western United States, RAWS stations have been set up to supplement traditional data collected at local airports. RAWS stations record hourly data for values such as temperature, humidity, wind speed, and amount of precipitation. In the event that a RAWS station was unavailable or there was not enough proximity to the corridor, the NWS archive was consulted and the nearest available airport was utilized. The archive of weather data is publicly available at *mesowest.utah.edu* in various database formats. All precipitation fell in the form of rain. It is understood that RAWS stations are not entirely accurate to the nearest one-hundredth of an inch, but generically they are still capable of discerning rain or no rain.

For the first iteration of the analysis, a restriction was placed on which hourly intervals could be considered affected by both rain and other non-recurring incidents. Unless the incident was reported such that its duration passed over an hourly interval, e.g. the incident occurred at 16:45 and took 30 minutes to clear, all incidents were designated within the hour that they actually occurred. Similarly, even though it has been commented that a wet road is arguably just as important as falling rain, something that will be focused on later within this dissertation, it was impossible to attribute the rain effects to intervals other than the ones that rain fell without adding a significant layer of subjectivity or making educated guesses about evaporation rates.

3.1.2 Selected Study Corridors

A total of seventeen study corridors were selected (Table 3.1) for analyses that were both representative of the state as a whole but also satisfying the following criteria:

1. Select multiple corridors for both the Southern (Los Angeles Basin) and Northern (San Francisco Bay Area) parts of the state.
2. Identify corridors with weather stations in close proximity. Weather can be highly localized, particularly in Southern California.
3. Avoid years where the weather was extreme, such as the rare event of December 2010 in Los Angeles when over 10 inches of rain was reported. This introduces the confounding effect of flooding and road closures, which is beyond the scope of this research.
4. Identify corridors with moderate congestion, as low volume corridors operating at free-flow during the peak hour might not show any delay. For corridors with heavy congestion, it might be hard to distinguish recurring and non-recurring delay.
5. Exclude freeway sections with faulty detectors. The detector data accuracy as reported in PeMS should exceed 75%, or preferably 90% wherever possible.
6. Prioritize creating a corridor at least 10 miles in length with functional detectors.
7. Utilize only typical weekdays (Tuesday, Wednesday and Thursday) to avoid atypical weekend flows and events.

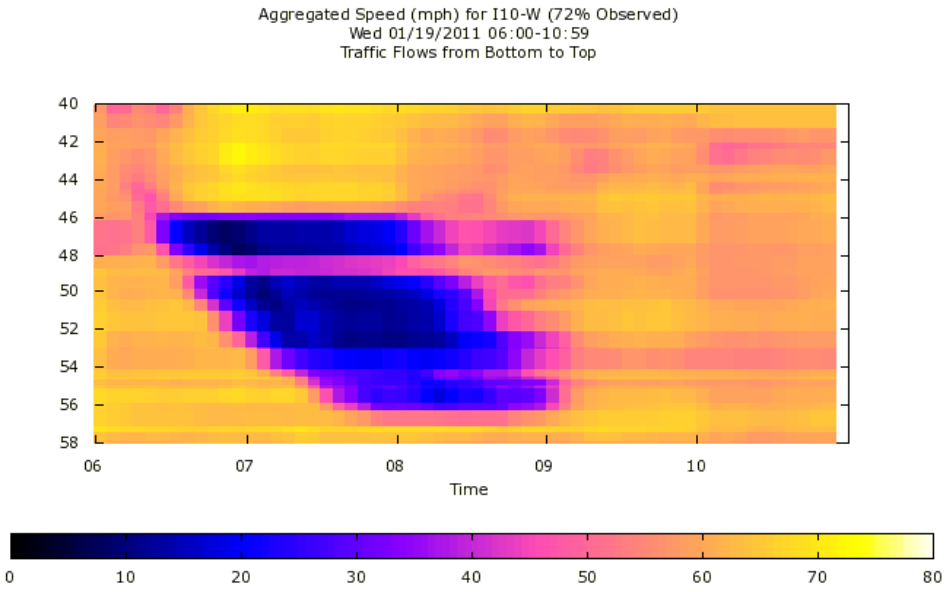
Table 3.1: Selected Study Corridors for Initial Work

Route	Direction	Corridor Length (miles)	City	Caltrans District	Study Period	Peak Period
CA 99	SB	11.6	Sacramento	3	Dec 06 - Feb 07	PM
CA 4	EB	13.7	Martinez	4	Dec 09- Mar 10	PM
I-580	EB	9.2	Oakland	4	Dec 09- Mar 10	PM
US 101	SB	11.0	Redwood City	4	Dec 09- Mar 10	PM
CA 41	SB	8.2	Fresno	6	Jan 10- Feb-10	AM
CA 60	WB	10.5	Hacienda Heights	7	Jan 05-Mar 05	PM
I-210	WB	13.0	Azusa	7	Jan 05-Mar 05	PM
I-105	EB	12.0	Hawthorne	7	Jan 05-Mar 05	PM
I-405	NB	12.6	Los Angeles	7	Jan 05-Mar 05	PM
I-710	NB	13.2	Compton	7	Jan 05-Mar 05	PM
I-10	EB	11.5	Ontario	8	Jan 11-Feb 11	AM
CA 99	NB	14.7	Stockton	10	Jan 10-Mar 10	AM
I-805	SB	15.8	San Diego	11	Jan 10-Feb 10	PM
CA 55	NB	9.0	Santa Ana	12	Dec 04-Feb 05	PM

3.1.3 Quality Assurance (Q.A.)

After running the procedure for all seventeen study corridors, a second round of examination was performed to address the problem of incidents affecting multiple freeway segments. For each corridor, on days of no rain where delay was very high but conditions were clear and dry, a speed profile for the morning commute was created by PeMS and compared with police incident logs for that particular day. For example, consider Figure 3.1, a PeMS speed profile for January 19, 2011.

Figure 3.1: Speed Profile of I-10 study corridor, January 19, 2011, AM Peak
All Lanes Aggregated



The dark area indicates an area of congestion that emanates from a possible non-recurring bottleneck between mileposts 45 and 46 (at milepost 48 there is a broken detector, which is why the speed briefly improves, this should be ignored). A check of the incident log of that day reveals that at 6:28 AM there was a five vehicle crash that took over one hour to clear exactly at milepost 45. In the first iteration of the procedure, if the crash did not occur within the freeway segment associated with each detector, it was classified as recurring. However, by examining corridor-wide speed profiles such as Figure 3.1 and discovering major incidents far downstream, this delay was correctly moved into the non-recurring / incident category. A review of all of the days for I-10 revealed two other days when formerly recurring delay was actually non-recurring / incident delay, and a third during a period of rain with no crashes that could be classified as non-recurring / weather delay.

3.1.4 Corridor Findings

The analysis results shown in Table 3.2 show a wide range for the weather related delay as a fraction of total delay. All values are shown in *vehicle-hours of delay per hour examined*. Weather delay ranged from 3% to 24% of the total delay, indicating that the effect of weather on congestion can differ significantly from place to place depending on both the typical weather and the amount of recurring delay on the freeway segment.

Table 3.2: Findings of Corridor Study

Route and City	Average Total Delay	Recurring Delay		Weather Delay		Incident Delay	
		Hours	%	Hours	%	Hours	%
I-405, Los Angeles	114.1	106.4	93.3%	3.4	3.0%	4.3	3.8%
I-210, Azusa	85.5	79.5	93.0%	2.6	3.0%	3.4	4.0%
CA 99 SB, Sacramento	67.6	60.4	89.3%	3.5	5.2%	3.7	5.5%
I-710, Compton	56.0	43.2	77.1%	7.5	13.4%	5.3	9.5%
I-105, Hawthorne	53.6	48.0	89.6%	2.9	5.4%	2.7	5.0%
CA 55, Santa Ana	34.6	31.2	90.2%	2.2	6.4%	1.2	3.5%
I-805, San Diego	27.8	17.9	64.4%	5.2	18.7%	4.7	16.9%
CA 4, Martinez	27.3	22.5	82.4%	3.5	12.8%	1.3	4.8%
CA 60, Hacienda Heights	26.0	19.4	74.6%	5.5	21.2%	1.1	4.2%
US 101, Redwood City	16.3	13.5	82.8%	2.2	13.5%	0.6	3.7%
I-580, Oakland	13.6	10.5	77.2%	2.5	18.4%	0.6	4.4%
I-10, Ontario	8.9	5.5	61.8%	1.7	19.1%	1.7	19.1%
CA 41, Fresno	1.9	1.4	73.7%	0.4	21.1%	0.1	5.3%
CA 99, Stockton	1.01	0.8	79.2%	0.2	19.8%	0.01	1.0%

Figure 3.2 shows the fraction of weather related delay to the total delay, with Figure 3.3 showing the same results normalizing for number of hours with rain, as some locations had more rain during their study periods than others. Following intuition, if congestion is severe all of the time, additional effects from incidents and weather will be small. On the far left of the graph, the graph depicts freeways with lighter overall congestion, such as Route 41 from Fresno and Route 99 from Stockton. On these corridors, traffic moves more smoothly on average and incidents are fairly rare. As such, one would expect weather to have a disproportionate effect on delay, in particular the specific weather effect from the first hour "slick road" phenomenon noted in the California driver's manual. Roads in the semi-arid area around Fresno can go weeks in between significant rain storms, creating a dangerous situation where oil deposits on the pavement surface liquefy. By contrast, many sites within the Los Angeles basin typically had high levels of recurring delay within the study period. For the I-405 corridor, average evening recurring delay was high enough that the effects of weather were only 3%, while the same rainfall events contributed 5.5% of the delay on the less congested I-105 nearby.

Similar results from both the I-210 and I-405 corridors suggest a lower bound for congestion due to weather for California freeways. In between the extremes were three sites in the San Francisco Bay Area. These sites had weather delays at or exceeding 10% while experiencing relatively low recurring delay compared to the Los Angeles sites.

Figure 3.2: Contribution of Rainy Hours to Delay versus Total Delay

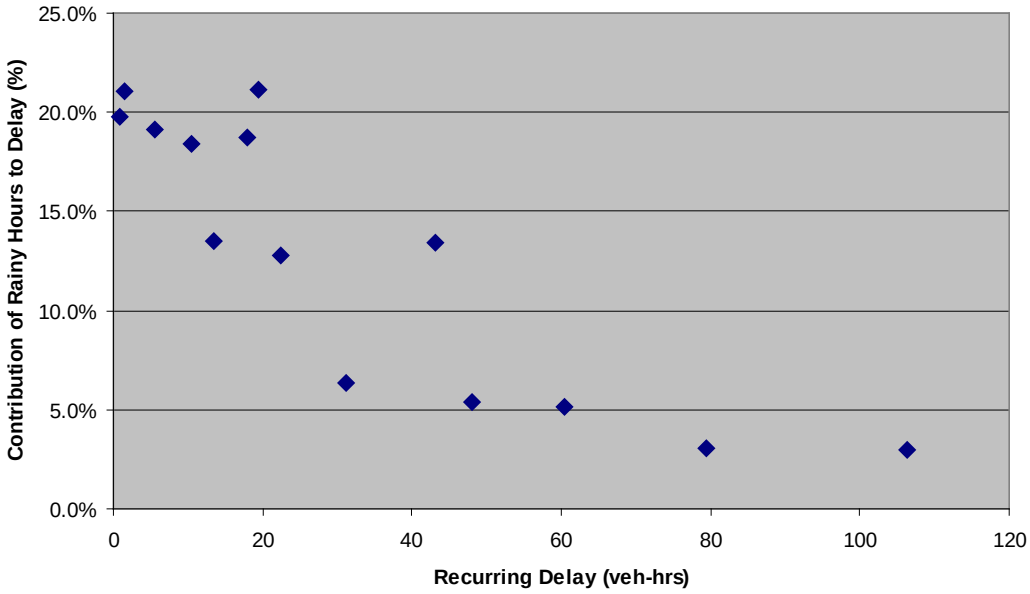
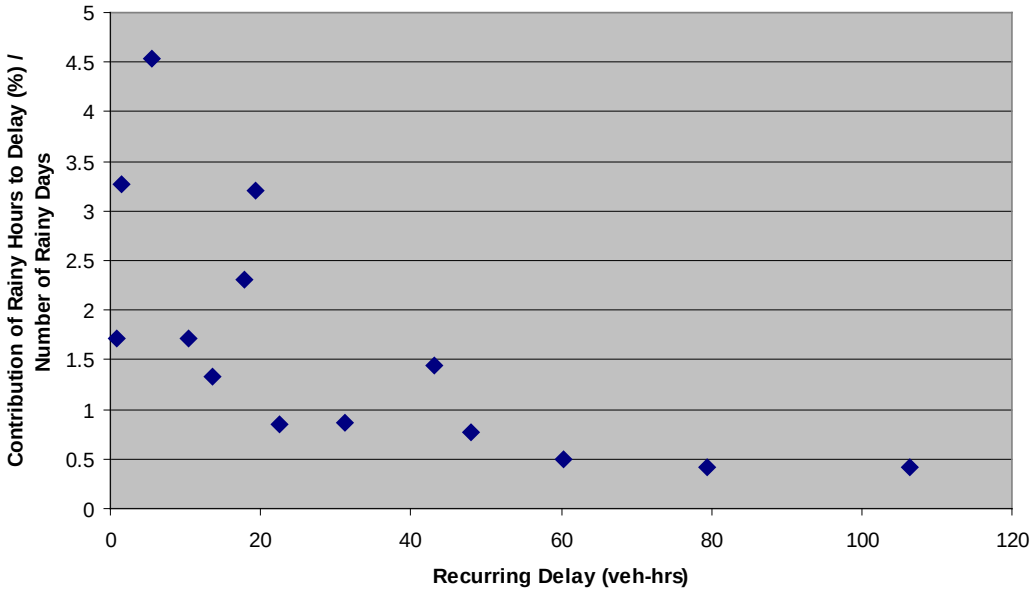


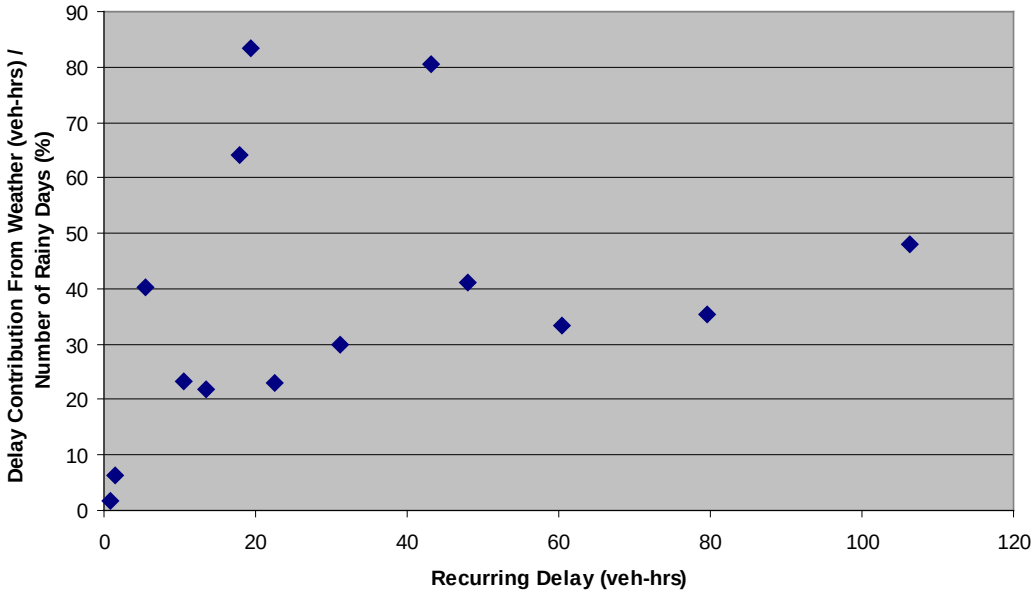
Figure 3.3: Contribution of Rainy Hours to Delay versus Total Delay Normalized by Hours of Rain



The section of I-580 in Oakland presented an intriguing result as heavy vehicles are not allowed on that segment. However, even in the absence of heavy vehicles and normalizing for number of rainy hours, the contribution of weather to total delay was higher on I-580 than on US 101 where there are no restrictions. Two sites within the LA Basin, CA 60 and I-710, had abnormally high percentages of delay due to weather as compared to their peer corridors along with very high truck percentages.

It has also been noted that even though the percentage contribution from rainy hours may be low at locations with very high recurring delay, the absolute contribution in vehicle-hours could be substantial. For example, delay due to rain on I-405 could be small in percentage, but high in absolute vehicle-hours as the 405 is a very heavily traveled road. Figure 3.4 shows this relationship, normalized by hours of rain. Although the lowest daily contribution in delay from rain in absolute hours was indeed in places of low recurring delay, the highest was not necessarily the busiest freeways. The study sites with the two highest delay contributions from weather in absolute vehicle-hours shown in the figure were CA 60 and I-710, roadways with very high truck percentages.

Figure 3.4: Contribution to Delay in Vehicle-Hours versus Recurring Delay Normalized by Hours of Rain



3.1.5 Data Concerns

Due to the lack of rain within the San Diego, Fresno, and Ontario corridors, the results are highly dependent on accurate reporting of incidents by the police and accurate speeds from PeMS. In San Diego on I-805, a very severe crash on January 12, 2010 formed a seven mile queue that did not dissipate for 3 hours. This resulted in the second highest non-recurring delay due to incidents of any corridor, including the much more congested I-405 in Los Angeles. Nevertheless, the weather effect for that specific corridor (18.7%)

was well within the pattern of correlation between recurring delay and % effect of weather on congestion.

One continuing concern was the ability to recognize the effect of incidents on the traffic stream, even after the Q.A. process. Observing major crashes required both identifying the crashes themselves as severe and following the shockwave backward through each detector. The severity of the crash was somewhat indicated by police descriptions by noting presence of emergency vehicles in addition to long "time to clear" values. For areas where the daily speeds were high, such as in San Diego, using engineering judgment to view the shockwaves caused by crashes was not difficult. The effects of crashes on multiple detectors on I-805 were identified relatively easily. However, the process is challenging on corridors with lower average speeds. For example, on I-405 in the Los Angeles area, it was nearly impossible to accurately detect all of the incident-related shockwaves traveling through the traffic stream even after looking at PeMS speed profiles and police incident logs, as average recurring speeds were less than 30 mph and very often below 20 mph. Thus, even after the Q.A. process, within the corridors of higher recurring delay there may be under-reporting of incident based non-recurring delay. This effect was magnified in the Los Angeles Basin by the complex interaction of freeway-to-freeway ramps. Severe crashes on one freeway in the vicinity of another can send shockwaves across multiple freeways that would be impossible to validate within the Q.A. process. Even with these concerns, the Q.A. procedure was still effective in the discovery of incidents within congested areas, which enhanced the effect of weather. By properly attributing the delay to incidents and removing them from the recurring category, it drove down the average recurring delay and increased the difference between the average recurring delay and delays due to both weather and incidents. In certain circumstances, such as I-405 and I-10 both in Los Angeles, the percentage contribution to delay due to weather doubled after the Q.A.

3.1.6 Discussion

In this section an extensive amount of historical traffic data from California freeways was analyzed to gain a better understanding of the proportion of traffic delay that can be directly attributed to weather and secondarily, incidents. Utilizing an established methodology, a congestion estimation model was developed to estimate vehicle delays directly attributed to rain on 17 urban freeway corridors. It was found that delay due to rain ranged from 3% to 25% of the total delay. The effects of weather vary significantly depending on both the type of weather and the amount of recurring delay on the freeway segment under study. The results showed that depending on the location weather is certainly a major factor in congestion and that an analysis of the performance of freeway bottleneck discharge would be a worthy endeavor.

3.2 Impact of Weather at Local Bottleneck

3.2.1 Approach and Data Collection

The second section of initial work was an examination of a local bottleneck conducted nearby in Pittsburg California on eastbound State Highway 4, known as the California Delta Highway. In this section, the freeway experiences a double lane drop from four to two, a demand surge from those exiting the terminal BART station directly to the west of bottleneck and a merge bottleneck after the lane drops from an on-ramp. A schematic of bottleneck is shown in Figure 3.5, showing the lane drops and relevant detectors. As one can imagine, there is severe congestion during the weekday afternoon peak hour. Figure 3.6, taken from PeMS, show both the contour plot (a graphical representation of speeds) and obvious slowed traffic. Darker colors indicate slower speeds as shown on the color bar below the plot. This contour plot is an average of the week from January 25 to January 27, 2012.

Figure 3.5: Schematic of SR 4 EB Pittsburg Bottleneck

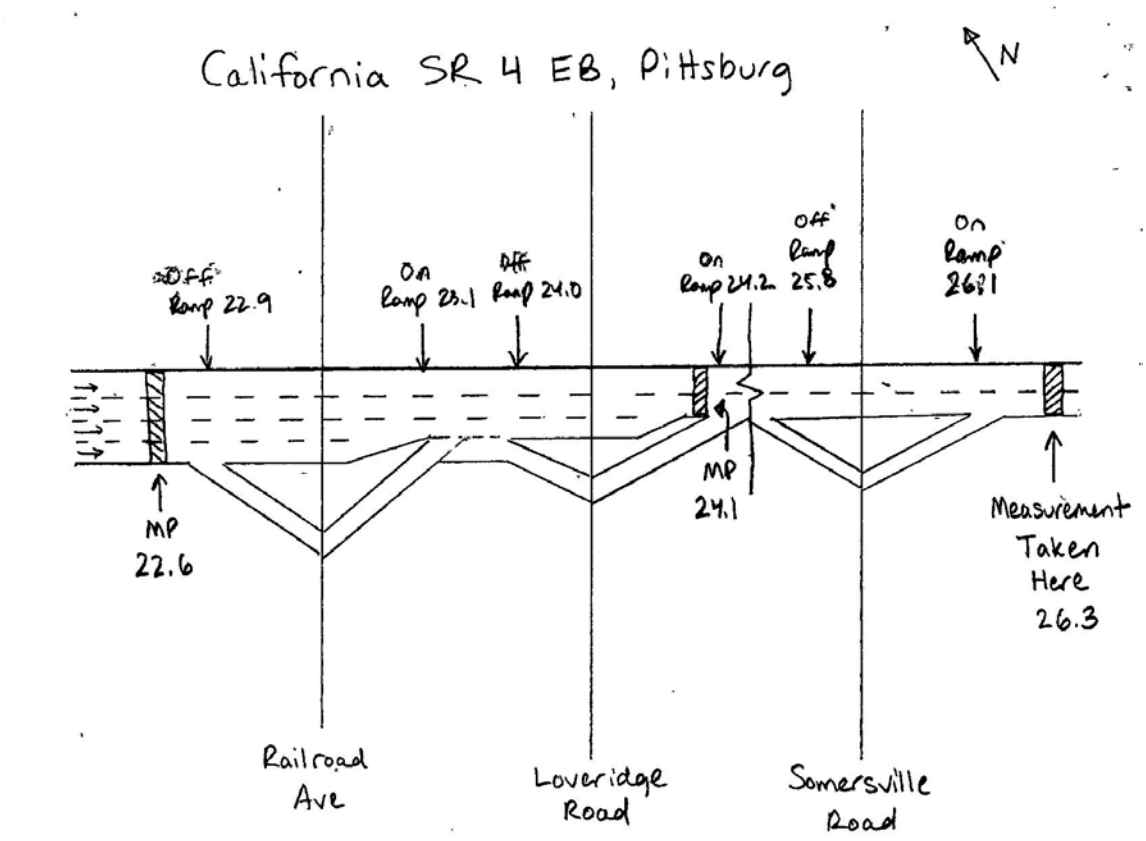
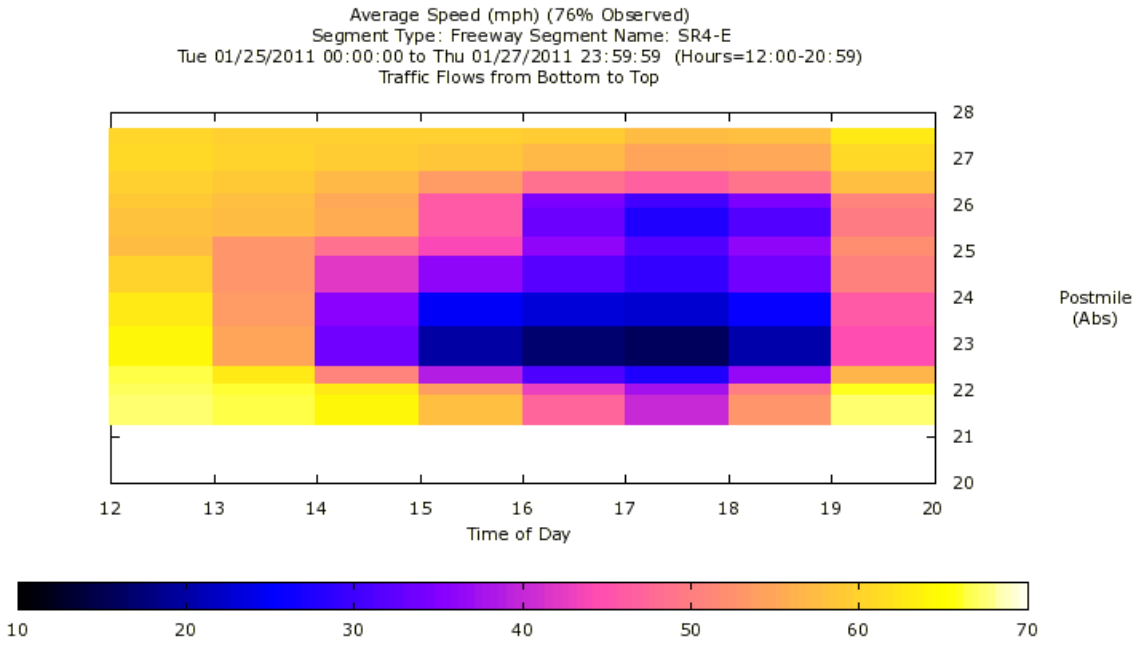


Figure 3.6: PeMS Contour Plot for Pittsburg Bottleneck



By looking at the contour plot on Figure 3.6 and comparing it with the Figure 3.5 schematic, a fairly complicated situation emerges. From 15:00-19:00, traffic speeds are always below 30mph to the west of the Loveridge bottleneck at milepost 24.2, with very slow speeds at the first lane drop from 16:00-18:00. However, there was also an hour (17:00-18:00) where the merge of the Somersville Road on-ramp also produced speeds slower than 40 mph. Therefore, it was decided to measure at a reliable detector downstream of the Somersville interchange.

Utilizing weather data and PeMS data, days during the PM peak were identified over the winters of 2010 and 2011 that had measurable rain from a nearby RAWS remote weather station. Five of these days were compared to their clear counterparts either 1 week before or 1 week after. Caution was taken to avoid days within the Christmas holiday period or the week following President's Day in February, as well as days influenced by severe crashes.

3.2.2 Local Bottleneck Findings

As expected, there were significant differences in flow measurement downstream of the bottleneck between the rainy days and the clear days. The following chart shows the flow rate per hour downstream of the bottleneck for both rainy and clear conditions for five PM peak periods during 2010 and 2011. Clear samples were taken on the same weekday either the following or previous week staying away from other rainy days or holiday periods. An additional sample was discarded due to the existence of a crash that significantly affected flow within the study period. Flow was reported as the average of the number of vehicles per hour from the time of typical bottleneck activation (14:00) to the end of the study period (20:00). Accompanying the results are the amounts of rain

leading up to and during the study period, as well as the most intense hour measured in inches per hour. Note that the difference is between the rainy days and the average of the clear days. Detailed weather data was taken from a nearby weather station at a local airport, Buchanan Field in Concord. Note lastly there are two lanes at this detector.

Table 3.3: Capacity Comparison of the Pittsburg Bottleneck during rain and clear conditions

Date	*Clear Downstream Flow (two lanes) Same Day, Different Week*	*Rainy Downstream Flow (two lanes) Taken On Actual Date*	*Absolute Difference From Clear Downstream Average*	*Rain (in.) 0:00-12:00*	*Rain (in.) 12:00-8:00*	*Max. Intensity*
Jan 20, 2010	*3,822*	*3,575*	*292 (7.5%)*	*1.33*	*0.19*	*0.16*
Jan 21, 2010	*3,835*	*3,239*	*628 (16.2%)*	*0.44*	*0.45*	*0.10*
Feb 23, 2010	*3,940*	*3,243*	*624 (16.1%)*	*0.09*	*0.37*	*0.07*
Feb 17, 2011	*3,860*	*3,545*	*322 (8.3%)*	*0.40*	*0.42*	*0.23*
March 15, 2011	*3,879*	*3,564*	*303 (7.8%)*	*0.00*	*0.29*	*0.13*
Average	*3,867*	*3,433*	*434 (11.2%)*			

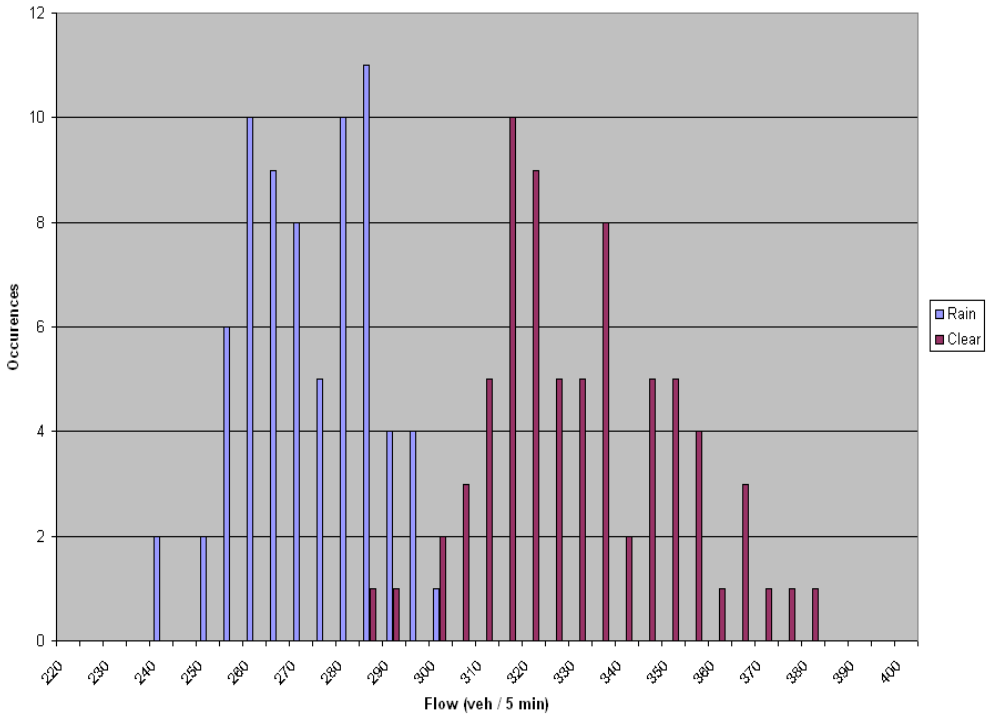
The table shows a consistent difference in the downstream flow of the bottleneck between the rainy days and the clear ones as well as strong consistency among the clear days. The day with the least rain during the study period had the smallest difference, and the two days with the steadiest rainfall over a long period (Jan 21, 2010 and Feb 2010) had the largest overall difference. February 2011 had half of the difference of Feb 2010 as most of the rain in 2011 fell in one hour early in the study period, allowing the traffic stream to recover later in the afternoon.

3.2.3 Statistical Testing of Findings

The results in Table 3.3 showed that the difference in downstream discharge can have significant variation. As previously stated, the two days with the highest difference in flow measured at the downstream detector between rain and clear were January 21, 2010 and February 23, 2010. Both of these days had steady measurable rain throughout the peak hour period, although neither of the two had any severe weather hours of over 0.2 inches per hour. Examining the flows in vehicles per lane per 5 minutes from 14:00 to 20:00 via a histogram, one can clearly see the difference. Figure 3.7 shows the histogram of the 5 minute flows for the rainy day of February 23, 2010 (rain) and a day during the

previous week when conditions were clear. Note that this clear day, February 17, 2010, is not one of the rainy days described above and is a year before it (February 17, 2011).

Figure 3.7: Histogram of Flows On 2/23/10 (rain) and 2/17/10 (clear)



For the comparison in Figure 3.7, the 5 minute flows look significantly lower on the rainy day than on the clear day in the previous week. It also may be that the flows are more bunched as well. To perform statistical analysis proving these assertions, an F-test was performed to check for equal variances and a T-test was performed for comparison of means. Again, the values used in this analysis are 5 minute flows from 14:00 to 20:00. The results are shown below in Table 3.4.

Table 3.4: Statistical Testing of Downstream Flow

Date	*F-Statistic For Equal Variances*	*Equal ?*	*T-Statistic For Comparison of Means*	*Significant Difference ? (95%)*
Jan 20, 2010	*3.21*	*Unequal*	*-5.14*	*Yes*
Jan 21, 2010	*0.49*	*Equal*	*-20.9*	*Yes*
Feb 23, 2010	*0.43*	*Equal*	*-20.2*	*Yes*
Feb 17, 2011	*5.12*	*Unequal*	*-5.69*	*Yes*
March 15, 2011	*1.45*	*Equal*	*-7.84*	*Yes*

While the F-test could not conclude that the bunching effect creating unequal variances, all of the days were highly significant in the difference of means tests. This indicates that rainy days do not need to have steady rain throughout the study period to have a statistically significant effect, nor does there need to be rain prior to the study period.

3.2.4 Discussion

The Pittsburg bottleneck showed an average of 11.2% reduction in flow at a detector downstream from the bottleneck on the five selected days, agreeing with Dehman's results seen in the literature review. Similar to the initial work on corridors, this rough study of a local bottleneck indicated that a more detailed study was appropriate. However, geometric limitations at Pittsburg prevented its use in the main body of the dissertation. The ramps of Somersville Road do not have detectors in the PeMS system, and thus it was impossible to subtract the off-ramp. However, it is unlikely that the ramp counts here would change from rainy to clear conditions, as Somersville Road does not lend itself to an alternate route to the freeway; there is no frontage road in this area and vehicles would have many traffic signals and a shopping plaza to travel through to get to the next exit. Any differences in the previous ramps (Railroad and Loveridge) during rain are handled by choosing a detector beyond the Somersville on-ramp, as drivers would re-enter at Somersville, although again it is fairly hard to construct an alternate route in this area. Accepting the limitation of the Somersville ramps, one could compare flows downstream against other days at the same bottleneck. However, one could not consider this downstream flow as true queue discharge without detectors on all the ramps within the bottleneck area. As such, the main body of the research examines a different set of bottlenecks in Southern California.

CHAPTER 4: DATA COLLECTION & METHODOLOGY

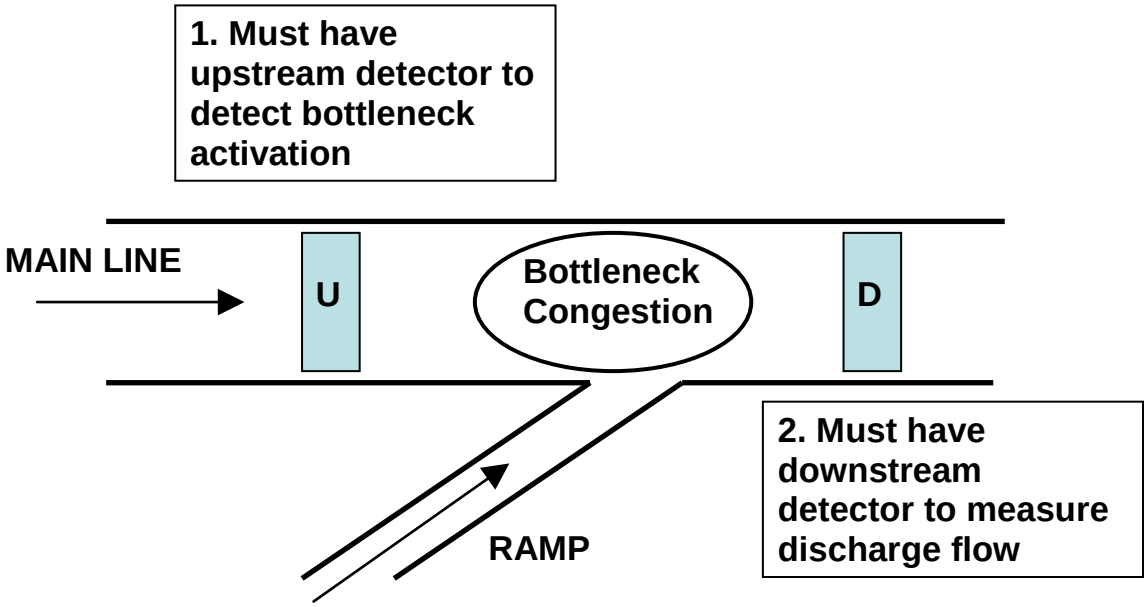
4.1 Data Collection & Site Selection

4.1.1 Merge Bottleneck Explained

The major focus of this dissertation is to build upon the initial work and quantify the effect of adverse weather on discharge flow from an active freeway bottleneck utilizing both archived traffic data and weather data. With enough samples, we will be able to draw conclusions on how the discharge flow changes when it rains based on specific weather conditions such as rainfall intensity, wind, and visibility. As such, the selection of bottlenecks and the data required are of the utmost importance, and considerable time was taken to find an appropriate set of bottlenecks within California.

Consider the figure below that shows a schematic of a merge bottleneck. When demand from the mainline and the ramp exceeds the capacity of the merge, cars will begin to slow down as not all of them can be accommodated at the same time, congestion begins and the bottleneck is considered active. Typically in this instance, congestion will propagate backward as a backwards-forming shockwave over many upstream detectors, forming a queue. In many cities, daily recurring congestion at merge bottlenecks can be substantial.

Figure 4.1: Merge Bottleneck Schematic



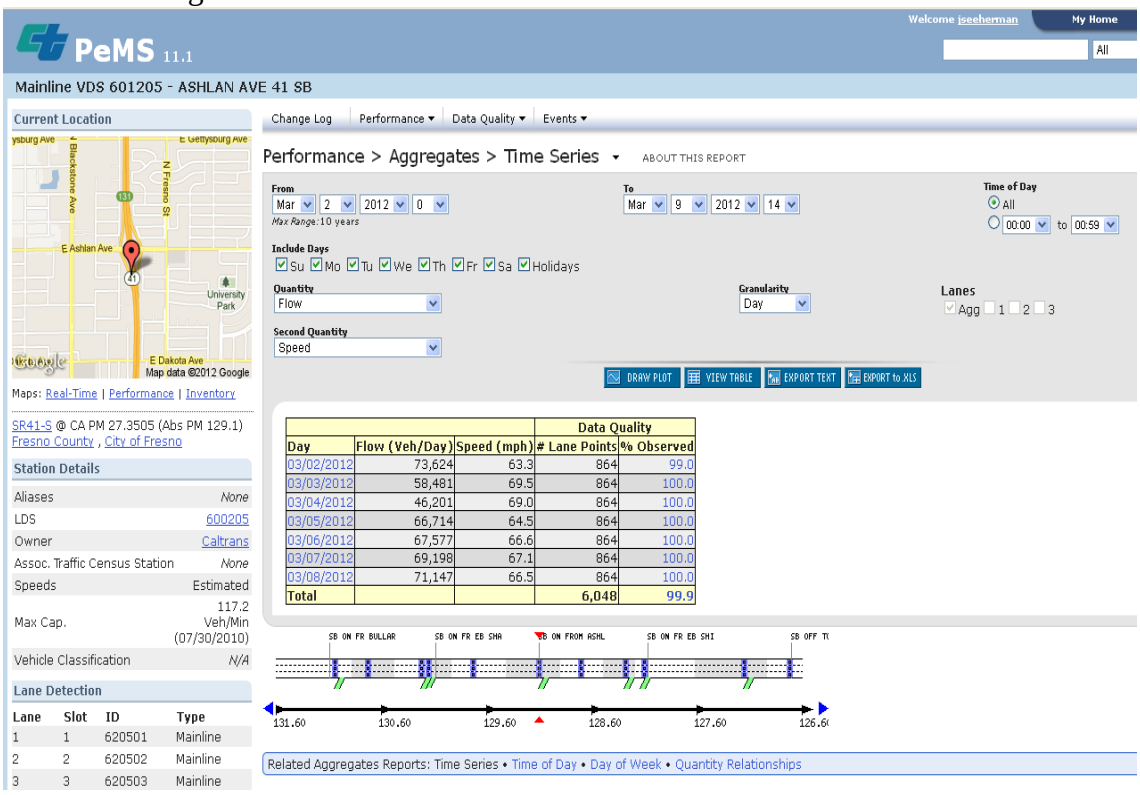
To properly calculate the queue discharge flow from an active bottleneck, two functional traffic detectors are required as shown in the figure above. First, a detector must be upstream from the actual merge geometry with no additional off-ramps in between. When the backwards-forming shockwave from the congestion reaches this detector, the percentage time the detector is covered by a vehicle, known as occupancy, can increase dramatically. As will be discussed further in methodology, a sharp increase in occupancy

generally indicates the onset of congestion. Occupancy of zero percent would be an empty freeway while occupancy approaching 70% would be a virtual parking lot or a situation where the freeway is closed and cars cannot move (100% aggregate is impossible unless all lanes have vehicles parked on their respective detectors). Second, a detector must be located downstream of congestion where the flow emerging from the bottleneck is moving freely. There cannot be any intervening on or off ramps unless these ramps also have detectors to add traffic existing or subtract traffic entering. Most importantly, again, the traffic must be moving freely across this downstream detector and not influenced by any additional congestion even further downstream.

4.1.2 PeMS Data

Traffic detector data in California are readily available via the public web-based graphical interface referred to earlier known as "PeMS". Within most urban areas there are PeMS detectors every ¼ to ½ mile for each lane, including carpool lanes. These detectors supply a database that creates a public catalogue of freeway traffic data including flows, detector occupancy (which could be translated in roadway density), as well as speeds and heavy vehicle percentages. PeMS provides data dating back to 2001, depending on the age of the detector, and additionally provides graphics documenting congestion and bottlenecks known as contour plots. An example of the PeMS database is shown below in Figure 4.2. In the figure, daily flows and average speeds are shown for SR 41 in Fresno County during a week in March 2012.

Figure 4.2: PeMS interface for a detector on Route 41 in Fresno



Additionally, PeMS provides information on other sources of non-recurrent delay including incidents and work zones. Incident-related congestion refers to congestion associated with crashes, breakdowns, debris, pedestrians in the right-of-way and other causes. To some degree, days with incidents generally disqualified themselves through a process of natural selection related to the rules already stated concerning the required two detectors. If a serious crash occurred upstream of the bottleneck, the congestion related to the crash tended to act as a metering device for the main line, particularly if a lane was blocked. Subsequently, the bottleneck to be analyzed would not activate due to reduced demand, noted by the lack of increase in occupancy at the detector upstream of the bottleneck proper. Conversely, if the crash occurred downstream of the bottleneck, it is likely that the congestion wave moving backward from the crash site would overwhelm the detector downstream of the bottleneck and the bottleneck discharge flow would not be able to be accurately measured. Nevertheless, the list of incidents from PeMS enabled the researcher to exclude those days. Since the analysis was performed for weekday peak periods, there was no interference from work zones or special events. Sites were selected to be far away from sporting venues.

4.1.3 Weather Data

While detailed traffic information has been available for about a decade, only recently has weather become publicly available at the level necessary for this analysis. The electronic public archive of the National Weather Service (NWS), available at *mesowest.utah.edu*, provides up-to-date data at all airport weather stations as well as the large network of automated remote weather stations. This has augmented the existing NWS website that provided access to remote stations. Although it is perceived that California is exclusively a dry and sunny place, California does in fact receive many days of rain and snow in a large portion of the state. Winter precipitation from November through March can be quite substantial at levels similar or higher than equivalent latitudes on the East Coast of the US. For example, during the winter season, precipitation levels in San Francisco (18.8” average) exceed those in Washington D.C. (15.7”).

When selecting the sites, as stated in the initial work it was of the utmost importance to have the weather stations as close to the bottlenecks as possible. Small microclimates do occur and the weather can be quite different within a distance of only a few miles.

4.1.4 Driver Population

The last piece in the data collection concerns the driver population. In an effort to control for driver behavior, the sites should be near each other regionally and have a fairly homogenous population of drivers that are regular commuters, avoiding tourist centers and sporting venues. A majority of the drivers that are traveling through the bottleneck should be familiar with the bottleneck. Therefore, in summary, the data collection should occur in an area where the freeway network is dense enough to have multiple merge bottlenecks in close proximity to weather stations, and those bottlenecks should be freestanding as not to be typically engulfed by other larger downstream bottlenecks.

4.2 Site Selection

With the guidelines for site selection described above, an exhaustive process was undertaken reviewing PeMS freeway corridor simulations to find recurring bottlenecks and subsequently examining local detectors and weather station proximity to determine if the bottlenecks were suitable for analysis. With all preferences considered, four recurring merge bottlenecks were selected in Orange County in Southern California, where there are approximately 35 days with rain per year. They are listed in the following table and shown in Figure 4.3 on Google Maps:

Table 4.1: List of Bottlenecks

Bottleneck Location	Freeway	Secondary Road	Direction	Time of Day	Weather Station
Irvine (#1)	I-405 San Diego Freeway	University Drive & Jeffrey Road	NB	AM	John Wayne Airport
Irvine (#2)	I-405 San Diego Freeway	University Drive & Jeffrey Road	SB	PM	John Wayne Airport
La Palma (#3) (Buena Park)	SR 91 Artesia Freeway	Valley View Street	EB	PM	Fullerton Airport
Fullerton (#4)	SR 57 Orange Freeway	Chapman Avenue	SB	PM	Fullerton Airport

Figure 4.3: Bottleneck Locations

4.3 Data Collection for Crashes and Other Incidents

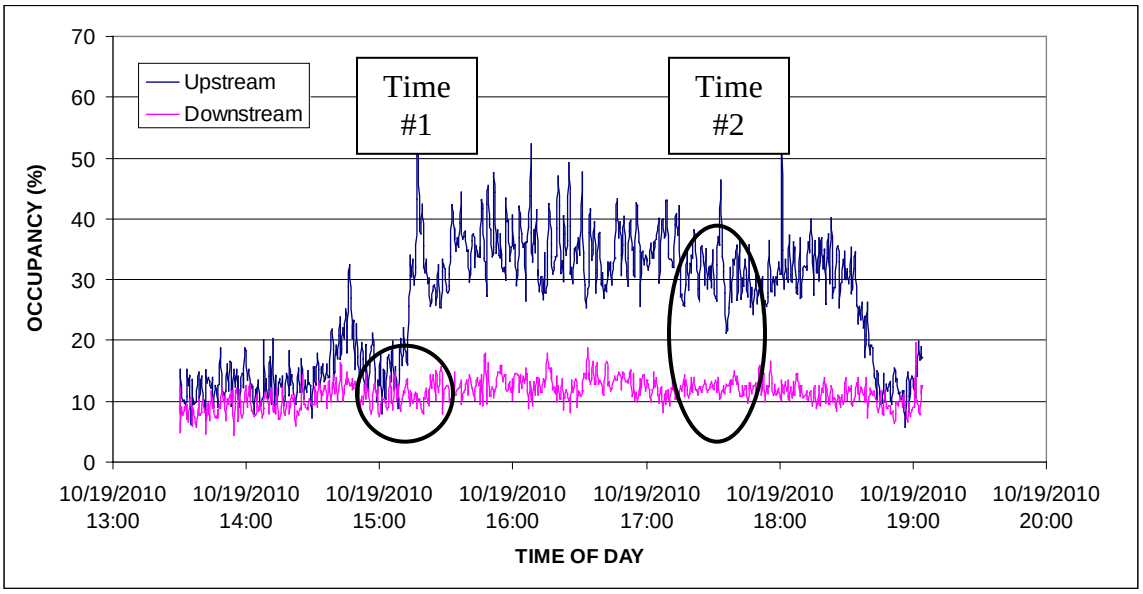
It has been discussed widely that there could be an increase of non-recurring congestion events such as crashes, breakdowns, or natural hazards when rain occurs on the freeway. To prove or disprove this theory, reports from the California Highway Patrol (CHP) were researched through the PeMS database. If the amount of crashes were dramatically increased during rain at the four sites, then it might be worth considering how to incorporate crashes into the overall experiment. The CHP reports were split into three different categories, injury collisions, property damage only (PDO) collisions, and all other CHP incidents (hazards). Other incidents could include a breakdown, debris on the roadway, a pedestrian or animal on the roadway, or flooding. For each peak period, incidents in these three categories were tallied in and around each bottleneck. It was then noted if there was light to moderate rain (<0.1 inch during the period) or heavy rain (>0.1) during that time. As a control, all of weekday peak periods in September and October of 2012, when there was no rain in Orange County, were also analyzed.

4.4 Methodology

The method for data collection involves utilizing an established procedure to recognize bottleneck activation which will allow for the measurement of discharge flow from said bottleneck. Weather data will be mapped to the congested period in 30-60 minute segments depending on the duration of the active bottleneck discharge. The procedure follows the work outlined in the research paper "Some Traffic Features at Freeway Bottlenecks" by Cassidy and Bertini (1999) utilizing the examination of cumulative curves. The objective is threefold: time of bottleneck activation, proof that the bottleneck has remained active further along in time, and measurement of queue discharge flow.

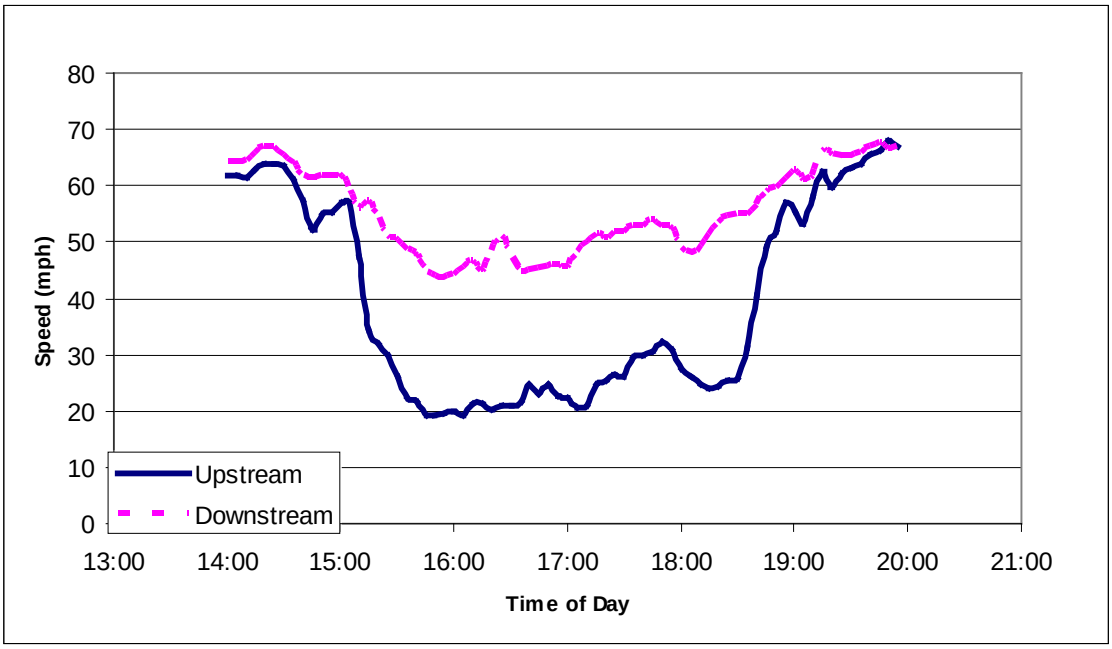
The following figure is a graph of occupancy at detectors upstream and downstream of the Bottleneck #4 in Fullerton. The data are taken in 30-second intervals and there are two specific time points that will be used for illustrating the presence of congestion.

Figure 4.4: Detector Occupancy on October 19, 2010
SR 57 SB at Chapman Avenue, Fullerton



As a rough approximation, we can convert occupancy to density. Assuming 20 feet per vehicle, occupancy of 20% would equate to roughly 52 vehicles per mile, a number significantly over the accepted typical density at capacity (45 veh/mile/lane) in the Highway Capacity Manual. However, the presence of occupancy over 20% is not sufficient for establishing a bottleneck but can alert a researcher to the potential presence of congestion. As a second piece of corroborating evidence, we can examine the speed curve for this bottleneck as well. Although we are not utilizing speeds exclusively, as speed is calculated and not measured, it can provide support to the presence of congestion.

Figure 4.5: Detector Speeds on October 19, 2010
SR 57 SB at Chapman Avenue, Fullerton



The first figure shows a dramatic increase in occupancy at the first time point which corresponds with a steep decrease in speed to as low as 20 miles per hour by 16:00. However, the detector downstream of the bottleneck does not decrease to lower than 45 miles per hour. Clearly there has been a change in the traffic stream at the first time point that warrants more investigation. This is where the procedure of examining cumulative occupancy and count curves will be utilized, as proposed by Cassidy and Bertini. The main theory behind cumulative curves is that during free flow (uncongested) conditions the accumulation of vehicle count and occupancy will track each other on a graph visible to the naked eye once a significant amount of background is removed. If the occupancy increases, one should see more vehicles being counted. Similarly, if the occupancy goes down, one should see the count of vehicles across the detector also go down; with enough background removed this decline will appear as a negative slope. In congestion the opposite occurs. If cumulative occupancy increases and the cumulative count decreases, this indicates that vehicles are in a congested state. As stated previously, the extreme of this situation is a freeway closure and all vehicles have to stop. In that scenario, occupancy would approach 70% and the count would remain flat, or with background flow removed, the count would show a rapid decrease. Changes from the uncongested regime where the cumulative count and occupancy track each other to the congested regime where the two curves oppose each other is a reliable indicator that a backwards-forming shockwave from an unknown cause of congestion has reached the detector in question. In the data collection that forms the basis for this dissertation, all days with other causes of non-recurring congestion, such as crashes or work zones, have been removed. At all four of our bottleneck sites, the cause for congestion is that demand has exceeded capacity at the merge of an on-ramp.

Let us look at the cumulative curves for the Fullerton Bottleneck for 10 minutes surrounding first time point at both the upstream and downstream detector. As a reminder, a significant amount of background flow and occupancy has been removed. In Figure 4.6 the background removed is 50 vehicles per 30 seconds, in Figure 4.7 it is 29 vehicles.

Figure 4.6: Upstream Detector Cumulative Curves
October 19, 2010 (15:13-15:22) - SR 57 SB at Chapman Avenue, Fullerton

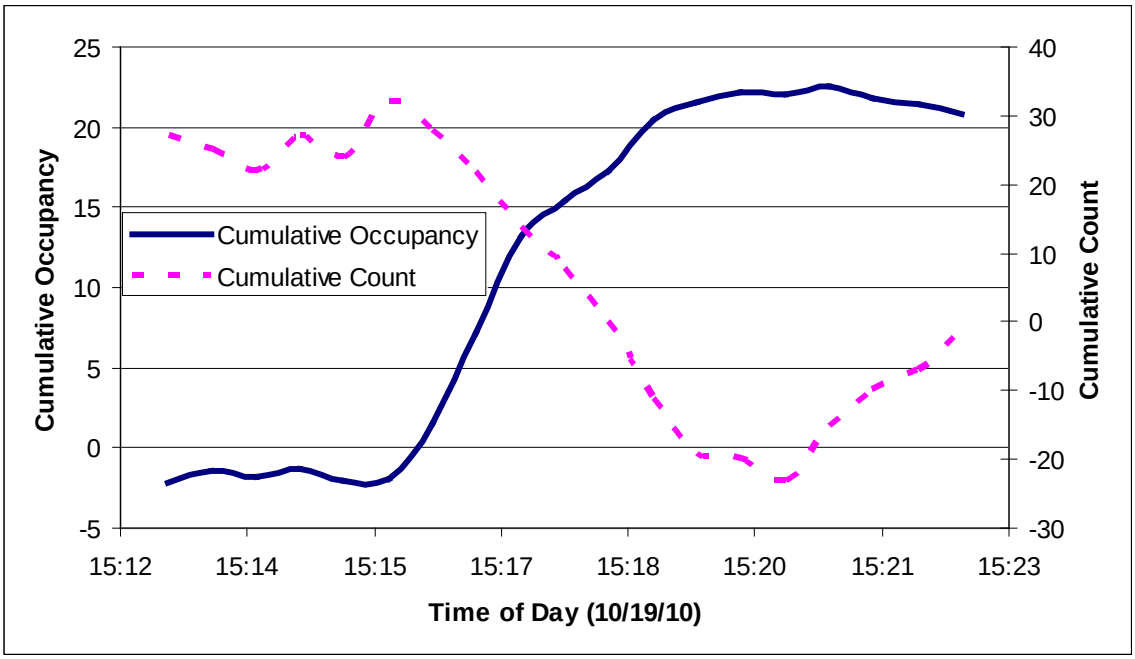
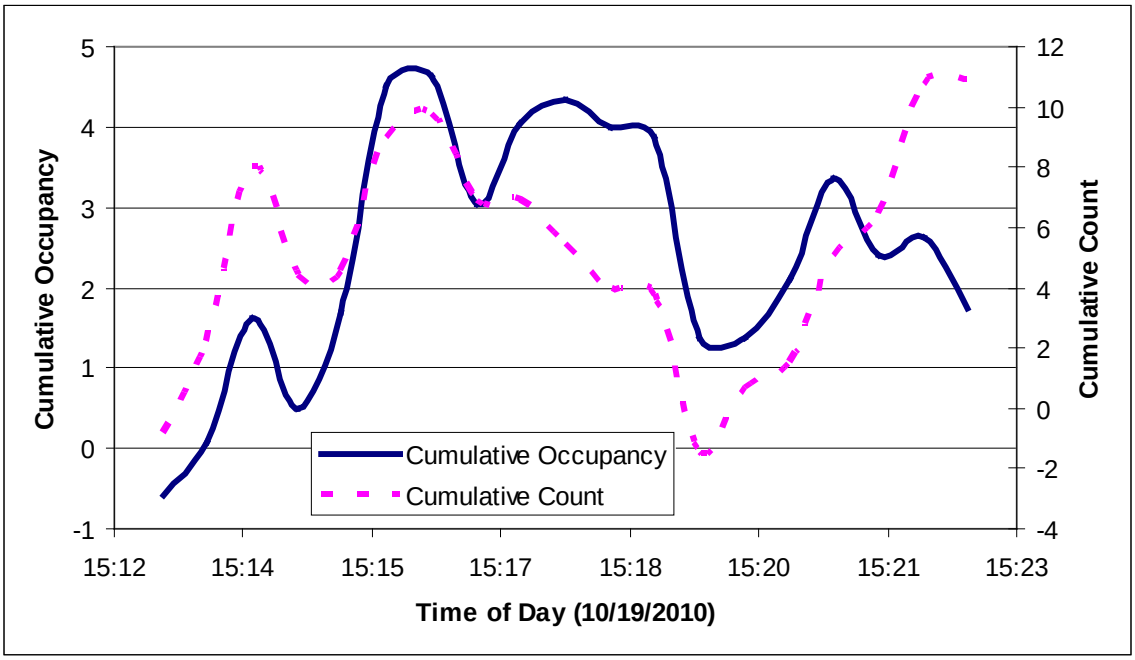


Figure 4.7: Downstream Detector Cumulative Curves
October 19, 2010 (15:13-15:22) - SR 57 SB at Chapman Avenue, Fullerton



As one can see in the above two diagrams, there is a clear difference in the characteristics of the traffic streams at the upstream and downstream detector. In Figure 4.6, which is upstream, there is an abrupt climb in cumulative occupancy at 15:15 which corresponds with a drop in the cumulative count, an indication of the detector being hit with a backwards-forming shockwave. This occurs at the same time as the drop in speed at the upstream detector and the spike in occupancy shown in Figures 4.4 and 4.5. However, as shown in Figure 4.7, the downstream detector does not show any ill effects of the onset of congestion. Rises in cumulative occupancy, indicating an increase in vehicles on top of the detector over a small period of time are equaled by an increase in cumulative count, telling the researcher that the traffic stream at this location is free-flowing and not congested.

Let us examine the detectors at the second time point. As shown above in Figure 4.4, at this time detector occupancy at the upstream detector has been above 30% for over 2 hours and downstream detector is remaining between 10 and 15%. In this instance, 56 vehicles have been removed in Figure 4.8, while 59 vehicles have been removed in Figure 4.9.

Figure 4.8: Upstream Detector Cumulative Curves
October 19, 2010 (17:30-17:36) - SR 57 SB at Chapman Avenue, Fullerton

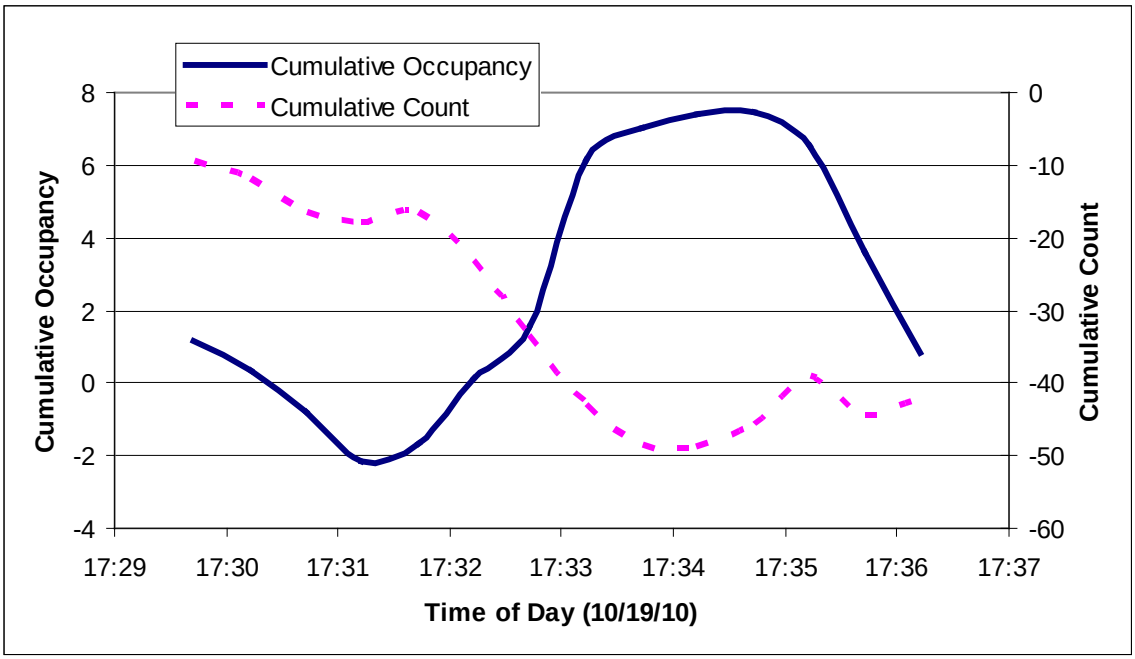
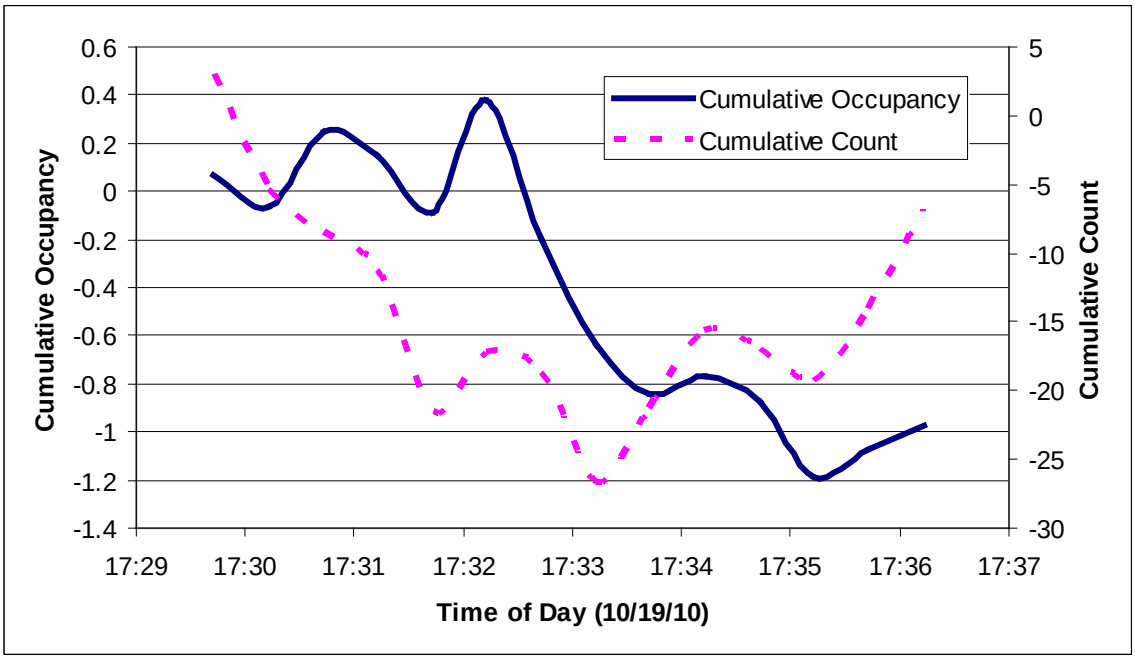


Figure 4.9: Downstream Detector Cumulative Curves
October 19, 2010 (17:30-17:36) - SR 57 SB at Chapman Avenue, Fullerton



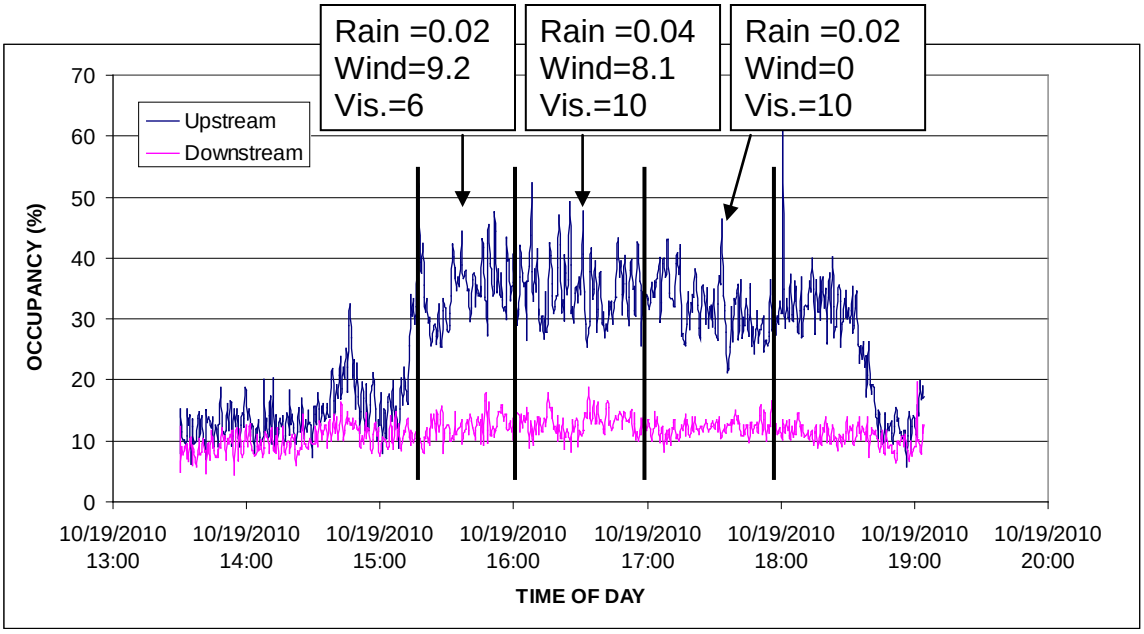
While the numerical values of the curves in Figures 4.8 & 4.9 differ from Figures 4.6 & 4.7, it is the shape and slopes of the curves that are show the state of the traffic stream. Again, at the upstream curve in Figure 4.8, we see the opposition of two curves, as the occupancy increases at 17:31, the cumulative count decreases, indicating the possible presence of congestion. The curves at the downstream detector in Figure 4.9 continue to rise and fall together, showing a free flow state.

From the cumulative curves at the two time points, one can make a conjecture about the state of the traffic stream in Fullerton on October 19, 2010. The bottleneck activated at approximately 15:15 and was still congested at 17:30 at the second time point. Examining Figure 4.4, there were very little changes in occupancy levels until 18:35 when the occupancy level upstream returned to levels seen by the downstream detector, indicating the passage of a backwards-forming recovery wave. Also, examining the occupancy of the downstream detector in Figure 4.4, occupancy stayed below 18% indicating that at no point during the congested period was the flow downstream affected negatively by a disturbance even further downstream. Therefore, it is appropriate to evaluate the performance of the bottleneck by measuring the count at the downstream detector from 15:15 to 18:35, which will be considered queue discharge flow from an active bottleneck.

Let us return to Figure 4.4 with the instantaneous occupancy and describe the procedure for mapping the weather data onto the discharge flow. The weather data is most reliably given per hour ending on the hour; during special weather events the forecaster may choose to include intermediate time points to indicate a specific situation like a ten minute downpour but this cannot be reliably used. Therefore, the weather data from the

hour at the onset of congestion is mapped to that hour with all subsequent full hours mapped to their corresponding weather data. If the final period before the end of congestion was the majority of the hour it was also typically included. For all work, 30 minutes was the shortest interval for analysis, still encompassing over 60 data points and eliminating noise from the 30-second data. The three weather variables used in this experiment were total rainfall (0 [dry] to 1 inch per hour [downpour]), maximum sustained wind (0 [calm] to 30 miles per hour [gale]), and lowest sustained visibility (10 miles [clear] to 0.25 miles [heavy fog]). The following figure shows how the weather data maps to the respective hours of congestion for the Fullerton Bottleneck on October 19, 2010. There are three data slices for this day, with each slice corresponding to the three weather variables and the average discharge flow as measured by the downstream detector at that time.

Figure 4.10: Bottleneck #4 (Fullerton) Weather Data Mapping, October 19, 2010



This data can be seen in the following table. The weather during congestion appears to be a steady drizzle with moderate winds to start, calming down to negligible with no visibility issues.

Table 4.2: Bottleneck #4 (Fullerton) Data for October 19, 2010

Time Period	Discharge Flow (veh/lane/hour)	Rainfall (in./hour)	Maximum Sustained Wind (mph)	Lowest Sustained Visibility (miles)
15:20-16:00	1,550	0.02	9.2	6
16:00-17:00	1,640	0.04	8.1	10
17:00-18:00	1,783	0.02	0	10

This process was repeated for every site and day that there was rain during or near the peak period. Thus a large data bank of discharge flows was constructed with a summary below in Table 4.3. For comparison with prior work the queue discharge during periods of rainfall will be compared with the average of periods of queue discharge with no rain. These results will be shown in Chapter 5.

Table 4.3: Summary of Data Collection

Bottleneck Site	Range of Discharge Flow (veh/lane/hour)	Range of Rainfall (in./hour)	Range of Sustained Wind (mph)	Range of Sustained Visibility (miles)	Number of Samples
Irvine NB I-405 AM	1612 - 2291	0 – 0.17	0 – 11.5	1.75 – 10	29
Irvine SB I-405 PM	1316 - 2129	0 – 0.40	0 – 24.2	0.75 – 10	52
La Palma SR 91 PM	1442 - 2283	0 – 0.31	0 – 12.7	0.5 – 10	48
Fullerton SR 57 PM	1247 - 1991	0 – 0.95	0 – 13.8	0.5 – 10	48

4.4.1 Pitfalls

It is well understood that there are limitations to this type of analysis. Particularly in periods of very light rain, it is not necessarily known when the rain actually falls during the hour; under a certain amount it isn't really raining but drizzling or misting. Similarly, the weather forecasters did have some leeway to take intermediate measurements which could lead to inconsistencies in the data for wind or visibility. Nevertheless, as will be seen, some significant conclusions will be able to be drawn from even this decidedly coarse data set.

CHAPTER 5: BASIC FINDINGS

5.1 Discharge Flow

After completing the analysis runs, the basic findings based on rainfall only are shown in Table 5.1 below and are compared to prior work by Dehman (2012) and the HCM (2010).

Table 5.1: Decrease in Discharge Flow (%) vs. Rainfall

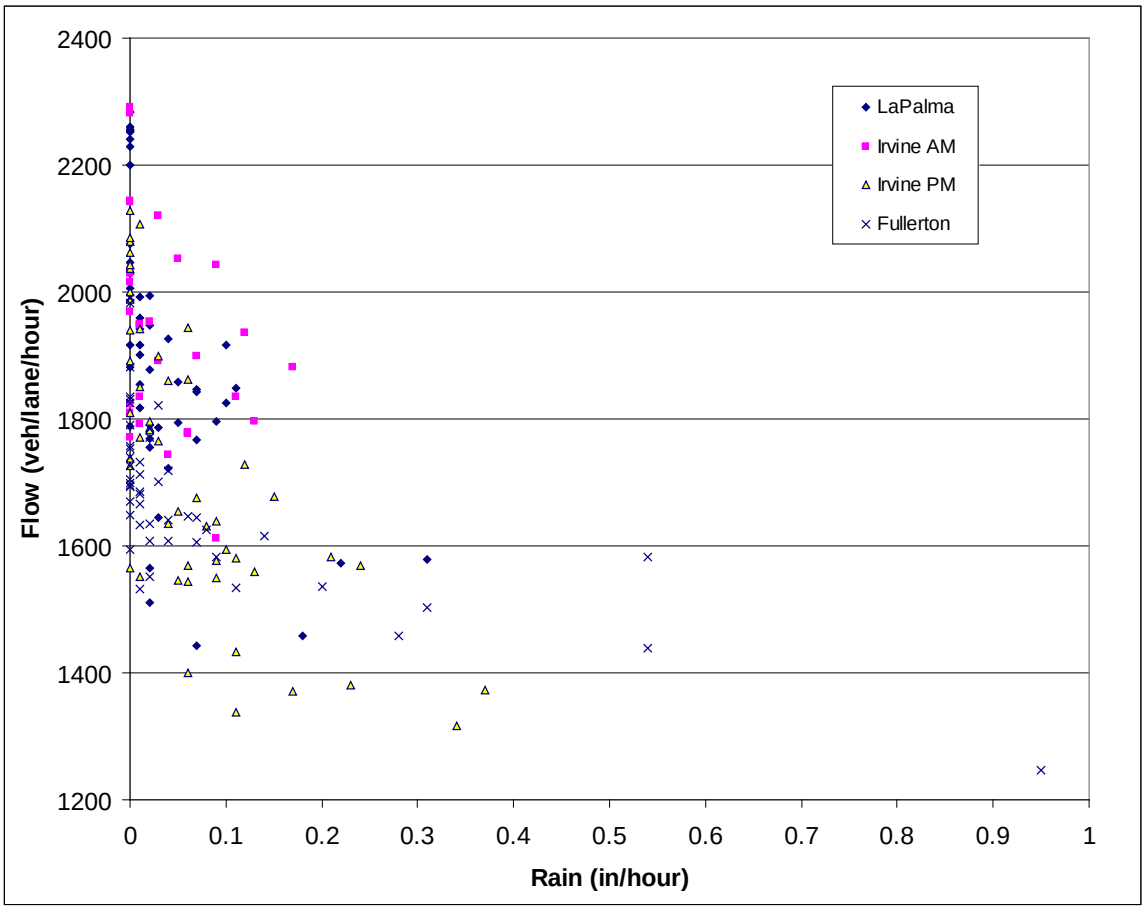
Bottleneck Location	Average Discharge Flow No Rain	Rainfall (inches/hour)		
		Drizzle (0.01-0.02)	Moderate (0.03-0.1)	Heavy (0.1+)
Irvine NB I-405 AM	2,007 veh/lane/hour	5.5%	6.3%	7.7%
Irvine SB I-405 PM	1,942	6.1%	14.1%	25.6%
La Palma SR 91 PM	2,115	12.8%	16.5%	27.1%
Fullerton SR 57 PM	1,768	5.7%	6.1%	16.7%
Average of All Sites	1,958	7.5%	10.8%	19.3%
Past Literature [Dehman]		5.4 to 12.5 %	11.5 to 18.3 %	
HCM Chapter 10			~10 %	~17 %

The above table shows with just one independent variable, rainfall intensity, the discharge flow decreases from the average queue discharge with no rain. Additionally, as comparing the flows to the prior work by Dehman and the Highway Capacity Manual, the percentages generally are within the range of the other works. Certainly one would expect that the decrease in discharge flow in Dehman's work would be smaller than found in this dissertation's research as Milwaukee enjoys over 125 days of precipitation (35 being snow) and one would hope that Wisconsin drivers would be more familiar with bad weather than drivers in Southern California. This appears to be case with heavy rainfall, but not for light or moderate rainfall.

One would note that the average discharge flow without rain in Fullerton is slightly lower than their counterparts in the other three sites and there are three potential reasons for this occurrence. The first is that this is the only site that has an unmetered high occupancy vehicle (HOV) entry lane, allowing HOV to bypass the meter and potentially causing extra congestion. The second is that downstream from the on-ramp on Chapman Ave is an open section of the HOV lane on the mainline, which means that vehicles may be trying to cross the mainline lanes to the HOV. Lastly, and perhaps most likely, the distance to the next ramp is the shortest of the four sites by a significant margin, perhaps creating a pseudo-weaving section between the on-ramp causing the congestion and the next downstream off-ramp even though the traffic is in a free-flow state by that next ramp.

In the above examination the results are similar to prior work which is a good foundation to build upon. However, the new area of exploration in this dissertation will be beyond the three simple discrete bins of comparing discharge flow with light, moderate, and heavy rain. The discrete bins mask what is a very large amount of scatter in the data. This scatter is not presented in any of the prior works, even if it was possibly present. Plotting all of the data points for each site reveals the scatter as shown in Figure 5.1. If one performed a simple linear regression for all of the data points combined, one would find the following result shown in Equation 2.

Figure 5.1: Raw Values of Discharge Flow for the Four Sites



Equation 2: Linear Regression with One Independent Variable (Rainfall Per Hour)

Discharge Flow [Qd] = 1,854 vehicles + (-1037.7) x (rainfall [r])
Adjusted R-Squared of 0.27

As stated previously in section 1.2, it is the contribution of this work that will seek to improve upon this fairly poor description of discharge flow. This work will attempt to use additional weather variables to create an improved continuous function describing the effect of adverse weather on queue discharge flow and create generic findings across all four bottlenecks.

5.2 Basic Findings: Incidents

The following table shows the results of a simple regression between the three types of incidents (injury collisions, PDO crashes, other incidents) and two categories of rain (light or heavy) as dummy variables. Statistically significant independent variables are highlighted in bold typeface.

Table 5.2: Results of Crash Analysis Linear Regression

Site	Type	Intercept	Light Rain	P-Value	Heavy Rain	P-Value
Irvine NB I-405 AM	Injury Crash	0.03	-0.04	0.36	0.04	0.45
	PDO Crash	0.20	0.02	0.87	0.05	0.72
	Other Incidents	0.06	-0.06	0.23	0.02	0.71
Irvine SB I-405 PM	Injury Crash	0.04	0.08	0.18	0.03	0.70
	PDO Crash	0.16	0.18	0.11	0.13	0.29
	Other Incidents	0.19	0.17	0.17	**0.45**	**0.0009**
La Palma SR 91 PM	Injury Crash	0.06	0.02	0.78	0.07	0.29
	PDO Crash	0.24	0.23	0.10	0.00	0.51
	Other Incidents	0.24	0.10	0.40	0.10	0.43
Fullerton SR 57 PM	Injury Crash	0.08	-0.03	0.70	0.05	0.47
	PDO Crash	0.39	0.07	0.68	0.34	0.06
	Other Incidents	0.27	-0.02	0.88	**0.29**	**0.03**

There were four sites with three types of incidents and two types of dependent variables, totaling twenty-four different possibilities where the interaction between rainfall and crashes/incidents could have been significant. Out of these twenty-four, in only two instances was there significance at the 95% confidence level, both “other incidents” in heavy rain. Examining the qualitative descriptions of these incidents, a majority were vehicle breakdowns, which is unlikely to indicate a level of causality with rain unless the rain is moving debris onto the road causing flat tires, similarly unlikely given the current strength of automobile tires. Out of the twenty-three non-collision hazards/incidents that had qualitative descriptions at the two sites, only two directly cited rain (flooding, rain-induced pothole) and an additional five involved debris. Given all of this information, it will be fairly safe to continue the experiment excluding days with crashes or incidents.

CHAPTER 6: HYPOTHESES

Five hypotheses will present relationships between discharge flow and adverse weather through the usage of three weather variables (rainfall, sustained wind, visibility). It is hoped that these hypotheses could offer significant improvement over the simple one-variable relationship shown above in Equation 2 and help to address the variability in discharge flow during light rain. The five hypotheses presented will be shown as follows:

1) Linear Regression – A simple regression between discharge flow and the three weather variables of rainfall, wind, and visibility.

2) Quadratic Regression – Similar to the first hypothesis with the addition of rainfall^2 as a regressor.

3) Fixed Effects Regression – A linear regression with dummy variables for light, medium, and heavy rain using no rain as a control. This effectively places the rainfall intensity portion of the regression into three discrete bins.

4) Fixed Effects with Continuous Correction – Similar to the third hypothesis but with a subtraction calculation to remove discontinuities in the three discrete bins.

5) Complex Hypothesis: Periods of queue discharge are placed in two groups, at the onset of congestion (Type 1) and all subsequent periods (Type 2). Each group has a specific set of regressors.

6.1 Simple Hypotheses (Hypotheses 1-4)

There will be four different simple regressions that will be evaluated in an attempt to gain a better understanding of the variability in discharge flow. As stated above, the first regression will have three regressors of rainfall intensity, wind speed, and visibility. It was found throughout some of the early regression runs that the wind variable was generally not significant unless it was raining. One could imagine a windy clear day not affecting driver behavior all that much, particularly since none of the bottlenecks are particularly exposed to wind like what might occur on a bridge on through a mountain pass. However, visibility can very much affect one's behavior in the absence of rain, such as a situation of dense fog. Hypothesis 1 is as follows:

Equation 3 (Hypothesis 1): Regression with all three variables, assuming independence between each period, with d0 representing the dummy for presence of rain

$$Qd = \alpha + \beta(\text{rain}[r]) + \gamma(\text{wind}\ [w])(d0) + \theta(\text{visibility}[v]) + \varepsilon$$

The natural extension of this analysis is to examine the quadratic form, as a curve might be a better descriptor of the data particularly in light rain. Hypothesis 2 follows this thread:

Equation 4 (Hypothesis 2): Expansion on Equation 3 with quadratic term

$Qd = \alpha + \beta r + \rho r^2 + \gamma w(d0) + \theta v + \varepsilon$

Hypotheses 3 and 4 utilize the concept of fixed effects to describe the first variable, rainfall. Instead of a continuous function, dummies were used to create three bins for light rain, moderate rain, and heavy rain with no rain as the control. These quantities used for assigning the bins were 0.01-0.05 inches for light rain, 0.06-0.1 inches for moderate rain, and >0.1 inches for heavy rain. For the second fixed effects regression an adjustment of this model was formed to create more of a sliding scale instead of using the 1-versus-0 dummies typically seen in with fixed effects. If a storm had a certain amount of rain, the value of the independent variable of the first bin would equal that amount of rain, the value of the independent variable for the second bin would be the amount of rain minus 0.05 inches or zero whichever was higher, and finally the value of the independent variable for the third bin would be the amount of rain minus 0.1 inches or zero whichever was higher. The third and fourth hypotheses are as follows:

Equation 5 (Hypothesis 3): Fixed Effects in Three Bins, where d1, d2, and d3 represent dummies for light, moderate, and heavy rain respectively

$Qd = \alpha + \beta(d1) + \rho(d2) + \sigma(d3) + \gamma w(d0) + \theta v + \varepsilon$

Equation 6 (Hypothesis 4): Fixed Effects in Three Bins incorporating actual rainfall instead of dummies

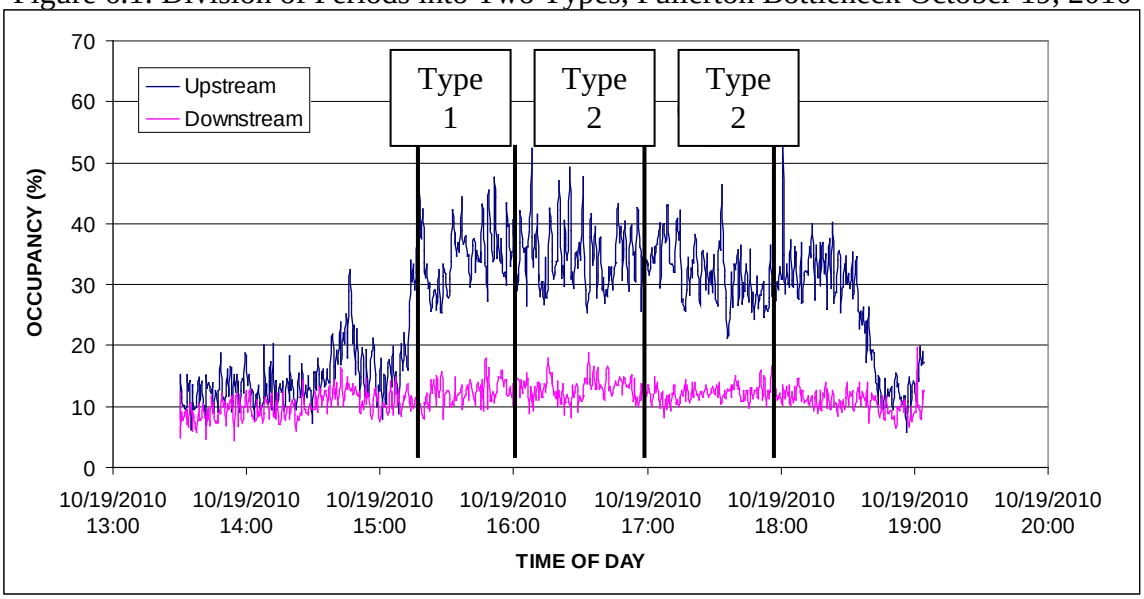
$Qd = \alpha + \beta(r) + \rho(r\text{-}0.05 \text{ or } 0) + \sigma(r - 0.1 \text{ or } 0) + \gamma w(d0) + \theta v + \varepsilon$

6.2 Complex Hypothesis (Hypothesis 5)

The fifth hypothesis, referred to as the complex hypothesis, attempts to be more fine-tuned than the prior four regressions. The first four hypotheses relied on the premise that all periods of both adverse weather and discharge flow from an active bottleneck were affected by the same variables. However, while the discharge flow at any given time is independent from other times, it is possible that certain periods of queue discharge are likely to be affected by different variables than other periods. Therefore, the complex hypothesis will try to extract some of these details.

Let us revisit the diagram that has been shown for the Fullerton Bottleneck. There were three periods of congestion whose queue discharge had been measured. The complex hypothesis break up these three periods into two different types; Type 1 is the first period after congestion starts and Type 2 applies to all subsequent periods. This is shown below in Figure 6.1.

Figure 6.1: Division of Periods into Two Types, Fullerton Bottleneck October 19, 2010



With the periods divided into two types, the complex hypothesis assigns a group of independent variables to each type. They are shown in the following table:

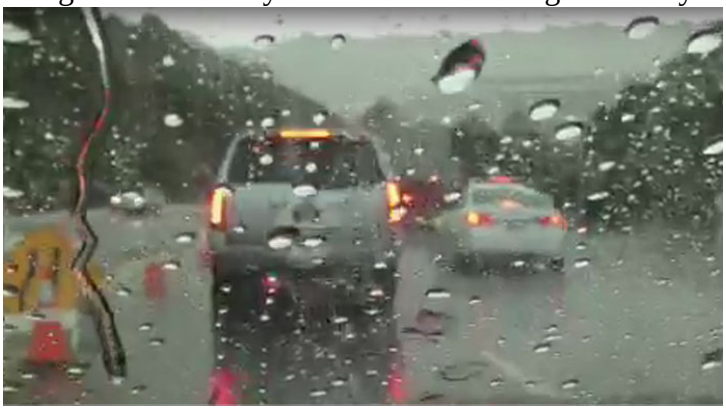
Table 6.1: Independent Variables by Period Type for Hypothesis 5

Period Type	Variables
Type 1 With Light Rain (rain < 0.05 per hour)	Current Weather + Prior Rain
Type 1 With Medium and Heavy Rain (rain > = 0.05 per hour)	Current Weather
Type 2	Differences in Weather Variables from Previous Period Only

The rationales behind the choices of variables are fairly intuitive. For Type 1, consider the two following photos of freeways after and during rainfall, Figures 6.2 and 6.3. The first photo, taken near the study sites on the Ventura Freeway (US 101), shows congestion, wet pavement and a rainbow, indicating that trace rain or drizzle might be falling. If the daily start of congestion occurs during this time, current weather characteristics will be important, but clearly the wetness of the pavement, made wet from prior heavy rain, could be as equally important. Drivers seeing the wet pavement while in free flow will be more apprehensive as they encounter and move through congestion based on prior experience driving in rain. However, in the second photo, taken in a work zone on San Diego Freeway (I-5) just north of San Diego, it is raining quite hard during congestion. The instantaneous characteristics are for more important than whatever weather occurred in the prior few hours.

Figure 6.2 – Drizzle, Rainbow, Wet Pavement on the Ventura Freeway

Figure 6.3 – Heavy Rain on the San Diego Freeway



In terms of Type 2 conditions, the queue has already formed and when drivers arrive at the bottleneck proper. In this case the complex hypothesis calls for a first-differences analysis, i.e. the change of discharge flow regressed on the change in weather conditions. While there are many reasons to use (or not to use) first-differences, in this situation the advantage over the conventional regression techniques of the first four hypotheses is that first-differences can eliminate issues of omitted variables such as geometry and any potential for serial correlation, as these biases fall out during the subtraction of the differences.

As a corollary to the complex hypothesis with Type 1 periods, one might conjecture that on a day of multiple periods of congestion in the final period of congestion the queue is similar to the initial state of congestion in that it is also short. Therefore, in these periods drivers might behave similarly to the initial Type 1 periods as those drivers will have a shorter time in the queue and therefore their memory of the weather during free-flow will be important. While the final periods of congestion would normally be treated as Type 2 period, it would be interesting to view their construction as a Type 1. Results under these two types will compared for this small subset of periods.

CHAPTER 7: HYPOTHESIS FINDINGS

7.1 Findings from Testing Hypotheses 1-4

The findings of the first hypothesis, the inclusion of all three weather variables as regressors (equation #3), are displayed in the following table. For this table and for all subsequent tables, significant independent variables (p-value < 0.05) are shown in bold typeface. Additionally, for all subsequent tables all values are shown with their p-values in parentheses.

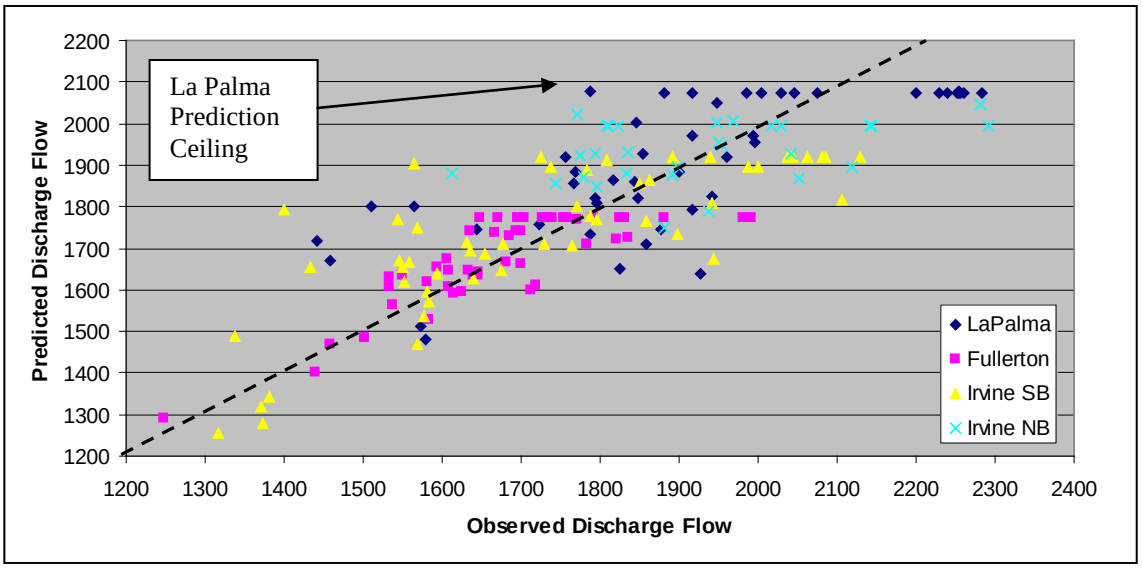
Table 7.1: Findings from Hypothesis 1

Bottleneck Site	Intercept	Rainfall (inches/hour)	Wind (miles/hour)	Visibility (miles)	Adjusted R^2
Irvine NB I-405 AM	2119	-1154.2 (0.21)	-14.7 (0.42)	-12.3 (0.32)	0.04
Irvine SB I-405 PM	1845	**-894.8** (0.02)	**-15.9** (0.002)	7.4 (0.65)	0.60
La Palma SR 91 PM	2096	**-1174.6** (0.01)	**-30.9** (0.0001)	-2.1 (0.83)	0.54
Fullerton SR 57 PM	1613	**-244.0** (0.007)	-7.5 (0.06)	**16.1** (0.0005)	0.65

For three out of the four sites, the regression revealed a value of rainfall intensity that was significant (p-value < 0.05). Although wind and visibility were significant in fewer sites, in every case when the variable was significant, the sign of the independent variable was correct. In the case of wind, as will be discussed later in this report, the sites with significant findings the driving direction of vehicles within the bottleneck (to the southeast) was directly into the wind. In terms of signs, one would expect that the increase in wind would result in a decrease in discharge flow (e.g. harder to see), while an increase in visibility would result in an increase in discharge (e.g. easier to see). At the Fullerton site, the site with the highest R-squared, two out of the three variables were highly significant (p-value < 0.01) and a third very close to being significant with a p-value of 0.06. The adjusted R-squared terms were above 0.50 with the exception of the first site, I-405 in Irvine in the morning. This was the only site in the AM hour and had the fewest amount of samples.

It is also helpful to view the data in a graphical form as a comparison between observed and predicted discharge flow in order to see the limitations of the regression. This plot is shown below in Figure 7.1. By being unable to accurately describe the variability at points of very low or no rainfall, the plot reveals a flat “ceiling” much the like the top of the thunderstorm cloud. For the La Palma bottleneck, the ceiling was at approximately 2075 vehicles, at Fullerton it was 1775 vehicles. Something else in addition to these three variables must be affecting the prediction, despite fairly decent adjusted R-squared values.

Figure 7.1: Predicted Vs. Observed Discharge Flow for Hypothesis 1



The set of findings from Table 7.1 will serve as the basis for comparison as we move along with the four remaining hypotheses. The following table shows the findings for Hypothesis 2 (equation #4) which includes a quadratic term and an extra column noting that while not all of the individual rain terms were significant, the joint significance test showed success with the PM sites.

Table 7.2: Findings from Hypothesis 2

Bottleneck Site	Int.	Rain	Rain^2	Wind (mph)	Visibility (miles)	Adj. R^2	Quad Joint Significance
Irvine NB I-405 AM	2181	-3924.2 (0.15)	17675.9 (0.27)	-8.9 (0.49)	-20.2 (0.29)	0.05	No
Irvine SB I-405 PM	1967	**-2677.5** (0.003)	**5061.7** (0.03)	**-14.7** (0.003)	-2.9 (0.80)	0.63	Yes
La Palma SR 91 PM	2134	**-2490.4** (0.05)	4809.9 (0.25)	**-29.0** (0.0004)	-5.3 (0.60)	0.54	Yes
Fullerton SR 57 PM	1606	-138.1 (0.56)	-124.6 (0.63)	-7.9 (0.06)	**16.7** (0.0006)	0.65	Yes

Although it was hypothesized that the quadratic term might improve the scatterplot from Figure 7.1, particularly addressing the variance during light rain, this proved not to be the case with no real changes in the adjusted R-squared term.

The following two tables show the findings for Hypotheses 3 and 4. Hypothesis 3, utilizing bins for each type of rain, showed modest improvement over the initial regression, while Hypothesis 4, the sliding scale regression, did not show noticeable benefit.

Table 7.3: Findings from Hypothesis 3

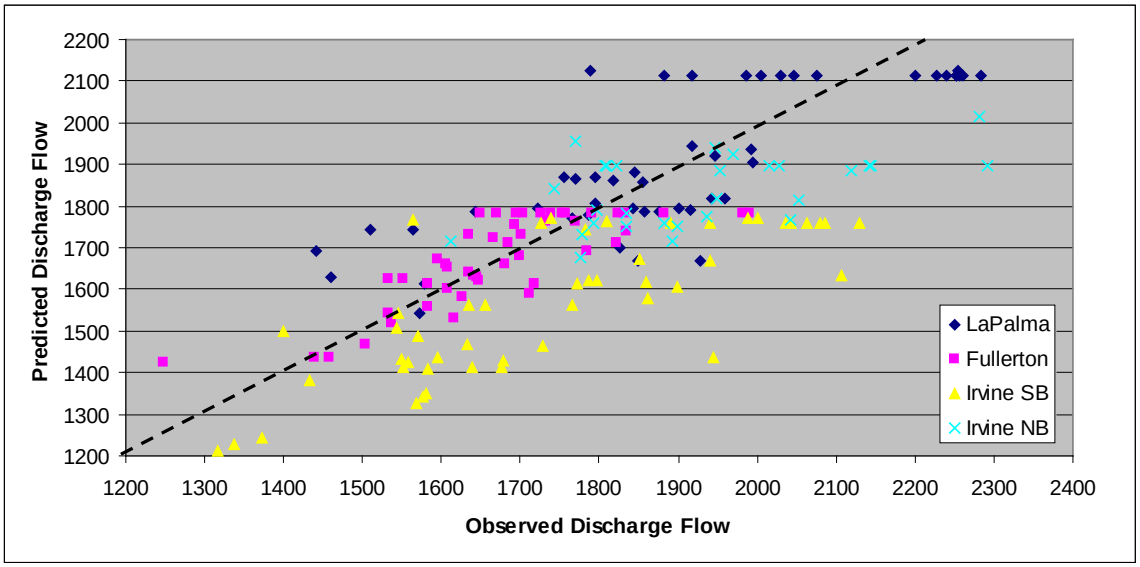
Bottleneck Site	Int.	Light Rain 0-0.05	Medium Rain 0.06-0.1	Heavy Rain > 0.1	Wind (mph)	Visibility (miles)	Adj. R^2
Irvine NB I-405 AM	2289	-123.4 (0.29)	**-306.1** (0.03)	-260.3 (0.09)	-9.4 (0.55)	-30.0 (0.13)	0.12
Irvine SB I-405 PM	1970	-25.4 (0.69)	**-181.6** (0.01)	**-253.4** (.004)	**-17.6** (0.002)	-3.0 (0.80)	0.63
La Palma SR 91 PM	2236	**-194.9** (0.02)	**-281.3** (0.004)	**-441.5** (0.0008)	**-21.7** (0.02)	-12.2 (0.22)	0.59
Fullerton SR 57 PM	1636	-21.1 (0.57)	-41.3 (0.43)	-107.3 (0.08)	-8.5 (0.09)	**14.8** (0.004)	0.61

Table 7.4: Findings from Hypothesis 4

Bottleneck Site	Int.	Rain	Medium Rain Adjustment	Heavy Rain Adjustment	Wind (mph)	Visibility (miles)	Adj. R^2
Irvine NB I-405 AM	2195	-1866.6 (0.58)	-927.5 (0.88)	4615.0 (0.47)	-14.3 (0.41)	-21.8 (0.28)	0.01
Irvine SB I-405 PM	1791	-2902.5 (0.14)	1983.2 (0.59)	585.1 (0.82)	-10.0 (0.11)	**15.5** (0.002)	0.23
La Palma SR 91 PM	2132	-4320.6 (0.06)	5240.8 (0.21)	-2161 (0.43)	**-24.2** (0.008)	-4.7 (0.64)	0.54
Fullerton SR 57 PM	1620	-276.3 (0.80)	-339.3 (0.87)	396.4 (0.75)	-7.2 (0.13)	**15.4** (0.003)	0.64

There is some merit to discussing the findings from Hypothesis 3 in Table 7.3. The use of bins makes good intuitive sense to the researcher and the layperson; subtract a fixed amount of traffic for each level of severity, adjust for wind and visibility. The adjusted R-squared term does improve slightly with the pesky AM site, although for the Fullerton site terms that had previously been significant in Hypothesis 1 were not in Hypotheses 3 and 4. Figure 7.2 is a graphical picture of the predicted versus actual results for Hypothesis 3.

Figure 7.2: Predicted Vs. Observed Discharge Flow for Hypothesis 3



The figure reveals, as would be expected, that there is still the same concern of the flat "top" for each site due to the inability to describe the variability with little or no rain. It appears that fixed effects underestimated the prediction more than the original regression, particularly for the Irvine site in the southbound (PM) direction. The scatter looks to be greater with fixed effects, although still generally near the "perfect prediction" dashed line.

7.2 Findings from Testing Hypothesis 5 (Complex Hypothesis)

7.2.1 Type 1 Periods with Light Rain

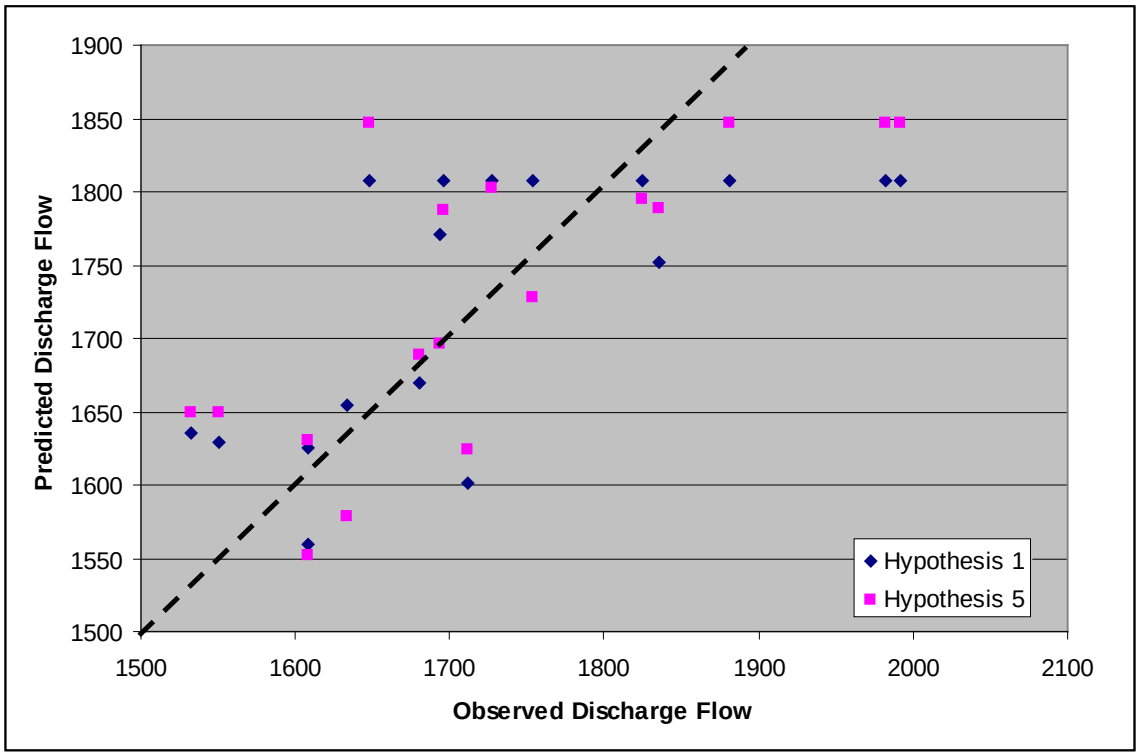
The findings of Hypothesis 5 are divided into three different parts reflecting Type 1 periods with light rain, Type 1 periods with heavy rain, and Type 2 periods. Recall that Type 1 periods were the first period of congestion; Hypothesis 5 stated that with light rain, the discharge flow prediction would be based upon both current conditions and prior rain, which in this case was the average rainfall for the 2 hours prior to congestion. Only two sites, Fullerton and La Palma, had sufficient sample size for this section. Table 7.5 shows the comparison between Hypothesis 1 (simple regression) and Hypothesis 5 which adds the effect of prior rain.

Table 7.5: Findings for Hypothesis 5, Type 1 Periods with Light Rain

Bottleneck Site	Hypothesis	Int.	Rainfall (in./hour)	Wind (mph)	Visibility (miles)	Prior Rainfall (in./hour)	Adjusted R^2
La Palma SR 91 PM	1	2071	-7207.1 (0.07)	-20.9 (0.23)	7.7 (0.59)	n/a	0.65
La Palma SR 91 PM	5	2058	-7283.9 (0.08)	-20.5 (0.26)	8.6 (0.57)	173.8 (0.77)	0.63
Fullerton SR 57 PM	1	1621	-2119.9 (0.63)	-6.7 (0.60)	18.6 (0.21)	n/a	0.32
Fullerton SR 57 PM	5	1652	-3538.4 (0.42)	-5.4 (0.66)	19.5 (0.17)	-1487.8 (0.14)	0.39

The addition of prior rain to the regression in Hypothesis 5 did not substantially improve predictions for queue discharge flow during the first period of congestion with light rainfall. There was some modest improvement at the Fullerton site, with improvements in adjusted R^2 and somewhat more significant independent variables, but still none of these variables were significant to the 90th percentile level, let alone the 95th percentile. Figure 7.3 compares the findings from the two periods. Again, one could see very marginal improvements, but nothing of statistical significance. The theory of prior rainfall and wet pavement was not proven in these findings. Perhaps a larger sample would improve this in the future. The plot in Figure 7.3 shows the difference between the predicted discharge flows with Hypothesis 1 and Hypothesis 5 for the Fullerton site. As there were some periods with no rain that did have rain the previous hour, there was some graphical improvement in flat top of the graph, but not of any major consequence.

Figure 7.3: Hypothesis 1 versus Hypothesis 5, Fullerton Site



7.2.2 Type 1 Periods with Moderate and Heavy Rain

Let us next examine the findings for the second part of Hypothesis 5 which examines first periods of queue discharge during rain that is moderate or heavy. Here, the advantage of segregating the periods of discharge will emerge in the ability to combine multiple study sites. Since these periods are dominated by the presence of steady rain, one could perform a log-likelihood ratio test for the combining of data to create a generic effect. The restricted and unrestricted models are shown in the following tables; in the unrestricted model the Fullerton site is used as a baseline for the geometry fixed effects variables to represent the difference in baseline discharge flow during clear conditions. For example, at the Irvine site there are four lanes and an HOV, while in La Palma there are five lanes plus HOV and the freeway merge occurs on a curve.

Table 7.6: Variables Included in Unrestricted Model

	Geometry Dummy	Rainfall	Wind	Visibility
13 degrees of freedom	Irvine	Fullerton	Fullerton	Fullerton
	La Palma	Irvine	Irvine	Irvine
		La Palma	La Palma	La Palma

Table 7.7: Variables for Fully Restricted Model

	Geometry	Rainfall	Wind	Visibility
5 degrees of freedom	None	One for All PM Sites	One for All PM Sites	One for All PM Sites

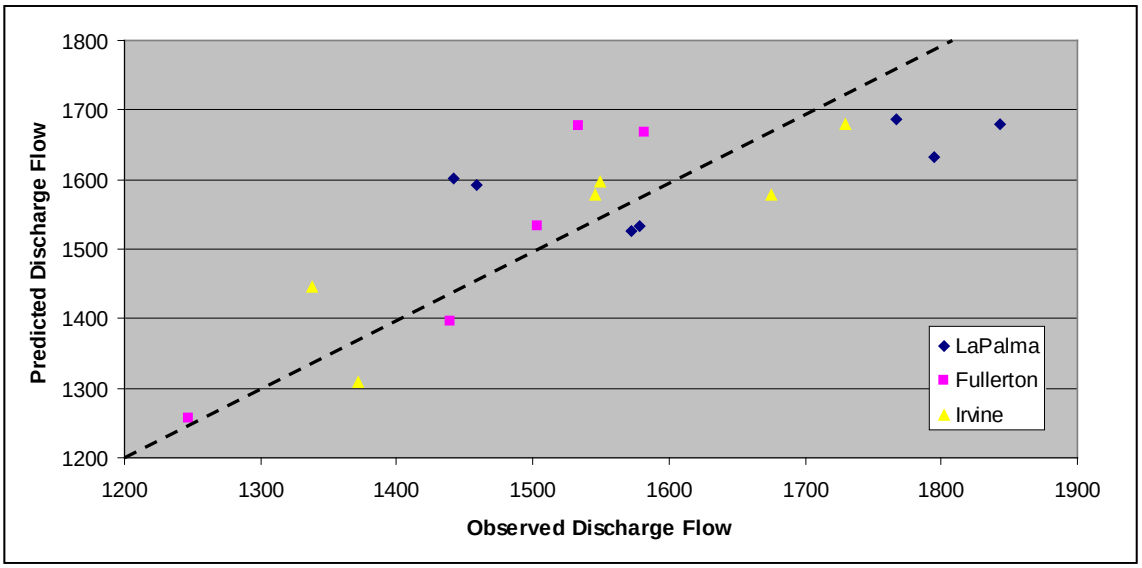
To pass the log-likelihood ratio test for restricting dependent variables, the AM site was separated from the other three sites, as it is established that the AM site performs slightly differently than the other three and there were very few AM 1st periods with moderate or heavy rain. In the unrestricted PM model, the log-likelihood value was -103.48, and the PM restricted the value was -107.87. This gives us a difference of 4.39, multiplied by 2 (as is required by the test) to 8.78 with 13 – 5 = 8 degrees of freedom. The 95% threshold for 8 degrees of freedom for the chi-squared is 15.5, meaning that one cannot conclude that the data comes to different sources and it is safe to perform the analysis as if they came from the same test site. The findings of combining the sites are in the following table:

Table 7.8: Discharge Flow during Moderate & High Rainfall in the 1st Period of Congestion

Intercept	Rainfall	Wind	Visibility	Adjusted R-squared
1754	-283.3 (0.07)	**-16.7** (0.008)	4.3 (0.79)	0.54

The above table presents a fairly noteworthy finding. Discharge flows from three different sites with geometric differences were able to be combined passing the log-likelihood ratio test for accepting restrictions. This union produced a fairly strong regression result with an adjusted r-squared exceeding 0.50. All three variables were of the correct sign with the wind variable highly significant (p-value < 0.01) and the rain variable modestly significant (p-value < 0.1). This supports the argument that during moderate or high rainfall the current weather conditions have a strong influence on the queue discharge from an active bottleneck. Figure 7.4 shows the predicted versus observed discharge flows for Hypothesis 5 for the first periods of discharge with moderate or heavy rain (rain > 0.05). There were points for all three sites on either side of the 1:1 line.

Figure 7.4 – Predicted Vs. Observed Discharge Flow for Hypothesis 5
Type 1 Periods with Rain > 0.05 inches/hour



7.2.3 Type 2 Periods

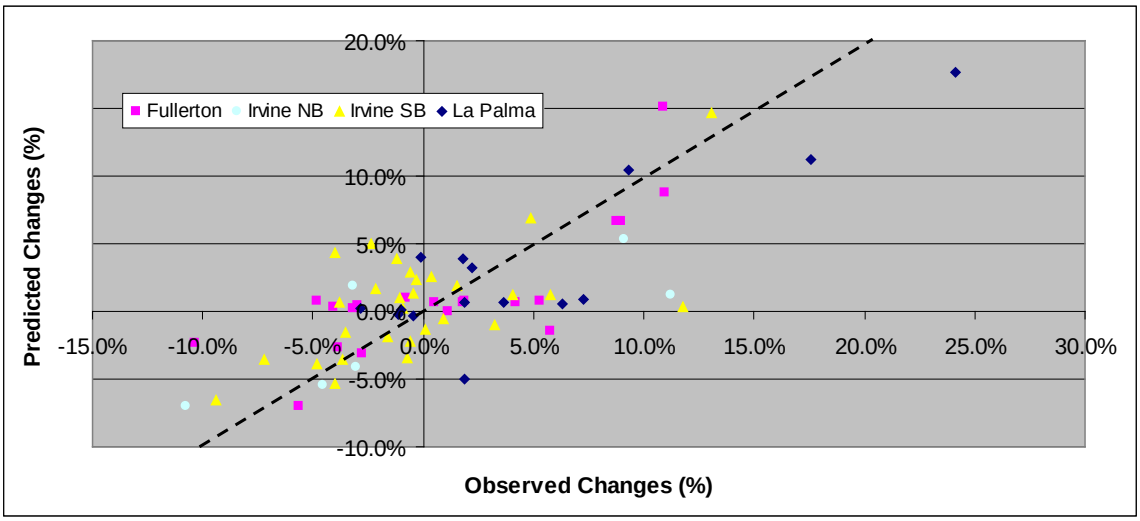
The last set of findings of the complex hypothesis concerns the Type 2 periods. To recap, these periods always follow the initial period of congestion, and therefore are "blind" in the sense that Type 2 periods depend only on the change in weather at that moment. As such, Type 2 periods for Hypothesis 5 utilize a differences analysis as opposed to a traditional regression to exploit the power of eliminating the effects of unobserved variables. The comparison between prediction and observed conditions will not be predictions utilizing the value of the absolute discharge flow from weather characteristics but instead predicting the change in discharge flow from the change in weather characteristics. Similar to the previous set of periods with queue discharge (Type 1 with moderate and heavy rain), additional power was sought by combining sites into a generic form utilizing the log-likelihood ratio test. A log-likelihood procedure was undertaken similar to the one for Type 1 with heavy rain; addition of new restrictions step-by-step until the 95% mark of the chi-squared test was breached. In this instance, restrictions were allowed for geometry, rainfall, and visibility, i.e. one could assume that rainfall had the same effect at all sites. The findings are shown in the following table, keeping in mind that the values are now expressed in percent change, as opposed to absolute change. For example, for every inch of additional rain, discharge flow from the bottleneck will decrease 18%.

Table 7.9: Discharge Flow Prediction for Hypothesis 5, Type 2 periods

Bottleneck Site	Intercept	Δ Rainfall (inches/hour)	Δ Wind (mph)	Δ Visibility (miles)	Adjusted R^2
Irvine NB I-405 AM	0.69%	**-17.99%** (0.03)	0.34% (0.34)	**0.95%** (0.0001)	0.55
Irvine SB I-405 PM			0.39% (0.11)		
La Palma SR 91 PM			**-0.73%** (0.04)		
Fullerton SR 57 PM			-0.02% (0.94)		

Both the rainfall and visibility measurements were not only generic but significant (p-value < 0.05), in the case of visibility highly significant (p-value < 0.01). In the case of wind the only significant variable was at the La Palma site, which would make sense as the angle of the merge faces directly into the primary wind direction of much of the rainfall, a topic that will be further explored in the discussion. The intercept also reflects an important finding that was found during the data collection, namely that if there are no changes in weather, the discharge will naturally improve by a small margin of approximately 0.7%. In that manner these findings differ from the previous ones in that changes in weather conditions are reflected directly by the coefficients of the independent variables. Therefore, a graphical representation of the predicted versus observed changes would show data points in all four quadrants of the graphical space. The following figure shows the results in graphical form:

Figure 7.5: Predicted Vs. Observed Discharge Flow for Hypothesis 5, Type 2 Periods



The points were fairly consistent in following the 1:1 ratio, with one real exception being a series of points from all different sites along the X-axis where the observed improvement was significantly larger than the predicted improvement. There was no discernable trend among these points, other than the observed outcome was unusual given the weather trends.

7.2.4 Comparison Between Hypothesis 5 Differences Analysis and Hypothesis 1 for Type 2 periods

A good check of whether the differences technique has been effective is to compare Hypothesis 5 against the Hypothesis 1 for predicting the flow for Type 2 periods. If the value from the differences technique in Hypothesis 5 equals or improves upon the predictions from Hypothesis 1, then generic power of the differences analysis would prove to be a superior method of analysis. Certainly a tool for examining all four sites would be more powerful than having equations for each individual site. The results of the comparison are shown in the following table:

Table 7.10: Comparison Between Hypothesis 5 and Hypothesis 1 for Type 2 Periods

Bottleneck Site	Average Error from Prediction to Observed	
	Hypothesis 5	Hypothesis 1
Irvine NB I-405 AM	-1.15 %	-1.64 %
Irvine SB I-405 PM	0.84 %	-1.44 %
La Palma SR 91 PM	-1.48 %	-9.41 %
Fullerton SR 57 PM	0.27 %	-2.59 %
Average For All Data Points Combined	0.01 %	- 3.50 %

For all sites the differences technique used in Hypothesis 5 performed better than Hypothesis 1 in predicting changes in queue discharge after the initial period of congestion. For the La Palma site, where all three variables were significant (p-value < 0.05) in Hypothesis 5, the improvement over Hypothesis 1 was over 7%. Most importantly, for examining all three sets of periods, Hypothesis 5 results were either competitive or superior to the Hypothesis 1. This could allow the analyst to utilize the power of the generic descriptions.

7.2.5 Last Period Comparison

As stated during the introduction of Hypothesis 5, there is a question of the last period of congestion during the daily peak. When examining the first period of congestion, the theoretical back stop to Hypothesis 5 is that prior weather conditions during free flow affect the bottleneck discharge rate at the onset of congestion because a majority of the vehicles entering the bottleneck during the first period experience free flow conditions almost up to the location of the bottleneck; a long queue has not formed yet. Therefore, during the final period of congestion a similar situation might also occur as the queue is also short similar to when congestion starts. Applying the Type 1 hypothesis for the periods at the end of the congestion as well as the beginning would help validate the theory involving the Type 1 periods.

Among the four sites, there were 15 one hour long periods of queue discharge at the end of congestion that came after at least 2 hours of congestion during the peak period. These periods were used to ensure that the queue length at the end of congestion was always significantly less than the maximum queue that occurred during one of the middle periods. With the limited sample size it was difficult to find a set of significant regressors from current and prior conditions, even after combining the sites. After examining the different variables and running sample regressions, the best group of independent variables was wind and visibility for current conditions, and rainfall from the previous hour as the prior weather condition. Note that this best group still had meager significance among the individual regressors, indicating perhaps that the discharge at the end of congestion performs in a far less uniform way than at the onset of congestion. Nevertheless, the signs of the variables were in the correct direction, and the values are shown in Table 7.11.

Table 7.11 – Discharge Flow Regression for Final Periods of Congestion

Intercept	Rainfall Prior Hour	Wind	Visibility	Adjusted R-squared
1793	- 922.6 (0.12)	- 2.82 (0.79)	8.90 (0.47)	0.27

Predicted values from this regression were compared with Hypothesis 5 and are shown in Table 7.12. In the second category ("two points removed") there were two data points where the difference between the observed and the predicted using Hypothesis 5 was sizable and they were removed to see if they skewed the comparison. Also, a sum of the absolute value of the differences is shown along side the simple sum of the differences.

Table 7.12: Comparison of Performance between the Hypothesis 5 and Regression from Table 7.11

Number of Samples		Difference between Observed and Predicted Hypothesis 5		Difference between Observed and Predicted Table 7.11 Regression	
		Integer Sum	Absolute Value Sum	Integer Sum	Absolute Value Sum
15	Sum	9.2 %	80.4 %	- 7.1 %	47.8 %
	Average	0.6 %	5.4 %	- 0.5 %	3.2 %
Two Pts. Removed 13	Sum	8.6 %	46.0 %	0.2 %	32.3 %
	Average	0.7 %	3.5 %	0.0 %	2.5 %

Even though the regression components were not significant, the regression from Table 7.11 did slightly outperform Hypothesis 5 in its prediction. However, averaging the difference from predicted to observed, Hypothesis 5 still ended up with an average difference of only 0.6% when all fifteen points were considered; the difference between the performance of Hypothesis 5 and the regression shown in Table 7.11 might not be

significant. Nevertheless, even though the Table 7.11 regression did not have strongly significant variables, it was still able to predict discharge flows as well as Hypothesis 5 and validates the thought process that the periods at the beginning and end of a long period of congestion might perform similarly.

7.3 Analysis of Temporal Variables

In addition to the above findings, there was a small investigation into the temporal variables (time-of-day and day-of-week) to see whether these were significant and worthy of consideration into the complex Hypothesis 5, i.e. is queue discharge affected by day of week or start time. It has been anecdotally observed by many individuals that Friday tends to the worse day for congestion but that might be exclusively due to demand and not bottleneck performance. Additionally, one could speculate that the performance of a merge during rainfall could get worse when it is dark outside. Since the data was taken during the wet season (winter), daylight hours were fairly short and many of the periods of congestion did bleed into night time hours. Tables 7.13 and 7.14 show the regression results for time of day and day of week for the start of congestion. For these two regressions, a fixed effects approach was utilized with Monday and 17:00 as the control. All other days and times are based upon those control points.

Table 7.13: Day of Week Regression for Discharge Flow for Three PM Sites

Variable	Value	P-Value	Sample Size
Intercept	2138		n/a
Tuesday	-113.3	0.17	14
Wednesday	**-182.1**	0.04	11
Thursday	-13.4	0.88	10
Friday	-128.4	0.10	20
Wind	**-26.8**	0.003	64
Visibility	**-29.0**	0.0008	64

Table 7.14: Time of Day Regression for Discharge Flow for Three PM Sites

Variable	Value	P-Value	Sample Size
Intercept	1818		n/a
Start Time = 12:00	-122.7	0.28	3
Start Time = 13:00	-195.1	0.13	2
Start Time = 14:00	-121.4	0.16	6
Start Time = 15:00	-63.8	0.31	19
Start Time = 16:00	-10.5	0.86	20
Start Time = 18:00	36.2	0.73	3
Wind	**-22.7**	0.0006	64
Visibility	16.6	0.08	64

Examining both tables, the first period of congestion starting on Wednesday was the only period significant to the 95% confidence interval as compared to congestion starting on Mondays, although sample size was fairly small. It is unclear why Wednesday (and not Friday) would have a lower amount of queue discharge at the start of congestion than the other days. There were no start times that were significantly different than those starting at 17:00. One might note that the earliest starting periods of congestion (12:00-14:00) had the lowest discharge rates, indicating perhaps that those drivers were unfamiliar with congestion at the three sites. Overall, there was not pervasive evidence that the temporal effects were significant enough for adjusting values in the main body of this dissertation.

CHAPTER 8: DISCUSSION AND FUTURE WORK

The effect of weather on freeways has long been a topic of study in civil engineering, however a review of past work has revealed that this has rarely has gone beyond idealized basic freeway segments. The primary reference at the national level, the Highway Capacity Manual, has conspicuously stayed away from addressing weather in depth and two primary studies cited in the manual (Ibrahim & Hall [1994], Brilon & Ponzlet [1996]) were conducted outside the United States and are almost 20 years old. For drivers, it is anecdotally understood that bad weather can make their daily commutes miserable, but there has been no real systemic thrust into how much longer or why it is taking longer. Within a daily commute most drivers will encounter periods of recurring congestion known as bottlenecks. Whether these are famous bottlenecks such the toll booths of the George Washington Bridge in New Jersey or something as simple as a steep grade, a local freeway merge or a poorly timed signal, these bottlenecks can define our commutes. Ease of passage through these bottlenecks can have a ripple effect on our mental health as well as financial implications associated with tardiness.

Along a parallel track, bad weather is common in virtually all parts of the country. Even in the Los Angeles basin, where the study area of this dissertation was located, there are still 35 days of rain on average and many more during years of a strong positive El Nino/Southern Oscillation, a macroscopic weather effect in the Pacific Ocean. With the advent of modern weather simulation, bad weather can be predicted up to 5 or even 7 days in advance. Knowing how freeways perform in bad weather can aid in traveler warnings and how much extra time motorists might anticipate needing to get to work or home.

8.1 Discussion of Findings

This dissertation's contribution has been to attempt to describe the performance of freeway merge bottlenecks during adverse weather by utilizing three weather variables (rainfall, wind, and visibility) commonly taken at local airport-based weather stations. Bottleneck performance is defined by measuring the queue discharge flow from each bottleneck; four different bottleneck sites in Orange County on I-405, SR 57, and SR 91 were examined. Relevant findings from the initial analysis are as follows:

1. Aggregating rainfall into bins for light, moderate and heavy rain, performance of the four bottlenecks generally agreed with prior work in Milwaukee, Wisconsin. Decrease in bottleneck performance ranged from 5% in drizzle to 27% in heavy rain.

2. An examination of the scatter plot of all points of queue discharge revealed a very high rate of variability during periods of light rain, particularly those less than 0.1 inches per hour. This was because other unknown independent variables beyond rainfall were having influence on discharge. Much of the new work in the dissertation was an attempt to explain this variation.

3. Four regression hypotheses were undertaken predicting queue discharge from an active bottleneck utilizing the three weather variables as regressors. Many of these regressions produced decent results with adjusted R-squared values greater than 0.60 in some instances. These regressions still did not accurately depict discharge flow very well with light rain, i.e. less than 0.05 inches per hour. However, at a majority of the sites at least two if not all three weather variables were statistically significant (p-value < 0.05). Regression utilizing a fixed effects design by placing rainfall quantity in bins did not substantively improve discharge prediction.

4. An examination of temporal effects including the start time of congestion and day-of-week variability did not find any significant effects with the exception of the discharge rate on Wednesday afternoons. There were no significant differences in discharge rate depending on the start time.

5. As a small addition, it was investigated whether the rate of incidents were statistically significantly higher during days with rain, as that would affect the ability to properly attribute reduced discharge to weather and not to incidents. Incidents were not found to be higher in rain on sections of freeway in and around the four bottlenecks.

Although a series of four regression hypotheses were undertaken with some success, a fifth more complex hypothesis for predicting queue discharge flow from an active bottleneck revealed that generic summations could be constructed for multiple different periods of rain. The periods of congestion were divided into three categories, onset of congestion with light rain, onset of congestion with heavy rain, and all subsequent periods. The first group was regressed on both current and prior weather conditions while the second group was only regressed on current conditions. The third group of periods used only the change in weather from the previous period in making the prediction. Findings relating to this fifth hypothesis are as follows:

6. Predictions for the first group of queue discharge observations, those at the onset of congestion with light rain, did not improve with the addition of prior rainfall for the two sites that had more than twenty samples. The author was hopeful that wet pavement would be a significant regressor, but it was not for this small sample.

7. Predictions for the second group of queue discharge observations, onset of congestion with moderate or heavy rain were equal to or better than in the previous hypotheses. However, by isolating these sites into a specific group with the fifth hypothesis, the data points were able to be combined from multiple sites, with restrictions on all three variables passing the log-likelihood ratio test. This led to a powerful generic description of bottleneck discharge flow at the onset of congestion with moderate to high rainfall.

8. Similar to the second grouping, the findings from the third portion of the fifth hypothesis (all subsequent periods after the onset of congestion) met or exceeded the performance of the simple predictions and also allowed for the power of the generic effect of combining data points. In this case, only rainfall and visibility were able to be restricted in order to satisfy the log-likelihood ratio test. This meant that for initial

periods of congestion with moderate or heavy rain as well as all subsequent periods of congestion, a generic finding was produced encompassing all of time periods across multiple sites. *This indicates a possible generic performance profile for merge bottlenecks in Orange County*.

9. It was considered that since initial periods of congestion during adverse weather could be dependent on prior weather conditions, perhaps the final period of congestion was also dependent on prior weather conditions as in both cases the queue length would be small as traffic remains in free-flow before arriving at the bottleneck proper. Although sample size was small with the number of final periods, it appears that incorporating prior conditions during this period does produce predictions at a level of quality equal to or higher than basing it alone on changes in current conditions.

8.2 Future Work

There are many different avenues to improve the power of the findings within this dissertation. These include more sites, additional variables, and different types of weather conditions. A list of possible directions is as follows:

1. In the process of creating the generic description of the Type 2 congested periods (third grouping of Hypothesis 5), it was discovered that placing restrictions on rainfall and visibility (e.g. the rainfall effect is the same at all four sites) passed the log-likelihood ratio test while the restriction on wind did not. At this time, a brief investigation was undertaken of the sites as well as wind direction during rainfall. At the Fullerton Airport, the average direction of wind during rain was 146 degrees, i.e. from the southeast. This direction blows straight into the front windshields of vehicles at one particular site, La Palma, which was not so coincidentally the site where wind was significant to a p-value less than 0.05. Perhaps the addition of wind direction might prove beneficial to future analysis.

2. The bottleneck sites were all located within one small county (Orange) and one Caltrans highway district (District 12). While rain is a common occurrence during the winter / wet season, much more rain falls in Central and Northern California. To expand on this analysis, it would be very interesting to examine two to three bottlenecks in the San Francisco Bay Area and compare findings to see whether the results of this dissertation are truly generic at a state-wide level or confined to Orange County. Additionally, the long periods of time between rainfalls can create very hazardous conditions as automobile fluids build up creating a slick surface when wet. The California driver's manual documents this problem, stating that "Many road pavements are the most slippery when it first starts to rain or snow because oil and dust have not washed away." This concern is especially the case in Southern California where rain events are less frequent. It is possible that this problem creates a more apprehensive driving populace within the study area as opposed to the Bay Area (or not).

3. Similarly, going back to 2005 there were only two periods of weather within the study area that had rainy conditions for more than 2 days in a row, January 19th through

the 22nd of 2010 and December 20th through the 22nd of 2010. However, north of California in Washington and Oregon periods of rain can last for many days and sometimes weeks during wet periods. By studying bottlenecks in these locations, such as Seattle and Portland, one might try to see whether performance changes day to day as the rain continues. Does the performance improve as drivers become used to the wet roadway, is there increased discharge as drivers in Washington and Oregon more familiar with wet weather in a general sense, or does the performance not vary significantly between the Pacific Northwest and California ?

4. This dissertation has focused on the effect of rain, mostly because frozen precipitation is absent in virtually all the urban areas of California. Nevertheless, it is quite obvious that snow would have an even stronger effect on bottleneck performance and would be very interesting to study. It is possible however that snow would create a congestion scenario where it would be impossible to measure bottleneck discharge flow as the entire corridor would be in a congested state.

5. The most significant future step would be to investigate changes in travel demand and whether trip start times might change if inclement weather is forecast. This would affect both affect queue length and overall delay. Some research has stated that there is no significant change in start time (Cools [2013] and Khattak [1997]) but others have seen a statistically significant change in travel plans (Kilpelainen [2007]). While these three studies rely on European data, there has been very little work on this topic in the United States. With the ultimate goal of being able to forecast trip time on the basis of weather (e.g. rain forecasted on Wednesday allow an extra 20 minutes), one would need to do a different investigation of queue length and queue duration during different intensities of adverse weather. It may be that while bottleneck performance may not vary by region, travel demand may actually vary quite a bit. One might consider a place where it snows one to three times per year, drastically affecting freeway performance, and a place where it snows twenty times per year, where commuters are less likely to change their behavior.

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