DONNER PASS IN CALIFORNIA: AN EXAMINATION OF EXTREME WEATHER AND THE POTENTIAL EFFECTS OF CLIMATE CHANGE ON TRAFFIC SAFETY

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ABSTRACT

A 50km section of the Interstate 80 freeway in California is among the snowiest sections of freeway in the world with over 900cm per year and is vital the transport of goods in and out of the state. Snowfall has been well documented as being a contributor to delays through the reduction of speeds, volumes, and the increase in disabled vehicles (incidents) and crashes. Focusing on incidents and crashes, climate change is predicted to reduce the number of severe snow events and convert many smaller and warmer snow events into rain only. It has been hypothesized that this will result in a significant reduction in incidents and crashes which will reduce both delays and costs. After creating a detailed profile of the snowfall within the 50km study area and an examination of existing crash rates, climate change predictions were applied to the profile by changing the snow to water ratios which resulted in a decrease of snowfall between 10% and 20%. However, the reduction in incidents and crashes was smaller, between 3% and 11%, as the lessening of the severity of snow events was counterbalanced by the increase in rain events.

1. INTRODUCTION

Long distance freight travel in the United States has long been divided between rail and trucking, with lower percentages for air, water, and pipelines. Although the trucking share per tonne-kilometer (42%) [1] is significantly lower than in the European Union (76%) [2], trucking is still the largest mode in the freight sector and the share would be much higher if one used the metric of value of goods instead of tonne-km. Consequently, the movement of freight by truck in the United States relies heavily on a 75000 km network of freeways constructed between 1945 and 1995. These roads are subject to the variability of severe weather, and weather generates significant concern for administrators of rural freeways particularly in the context of climate change. To maintain the freeway network for movement of freight as well as for passenger cars and tourism, this paper focuses on the effect of snowfall in a specific section of freeway within California known as Donner Pass. The purpose of this paper is twofold; a) to summarize historical snowfall and crash rates within Donner Pass, a location of extreme snowfall, and b) to attempt to predict the effect of climate change projections on future trends in crashes and vehicle breakdowns. Analysis of a freeway with such an extraordinary rate of snowfall as compared to most other study areas will prove a valuable addition to the knowledge base of traffic safety.

2. BACKGROUND

2.1 Literature Review

There has been significant research of the effect of snow on both traffic safety but without the context of climate change. Within public health, Eisenberg [3,4] has published two macroscopic studies on the effect of weather on crash rates using nationwide data. The first found a curious conclusion that not only does the crash rate increase during rain and snow but the first clear day after the storm the crash rate drops below normal. In his second paper, Eisenberg calculated the incident rate ratio (IRR) between snow and clear days, finding an IRR of 0.93 for fatal incidents, but 1.23 for crashes overall and 1.45 for property damage only (PDO) crashes. An additional finding found that the first snow of the year was significantly worse, particularly among elderly drivers. However, these examinations included areas where snow is much less common than in the study area of this paper.

Civil engineering research on snow and traffic safety has tended to focus on specific locations. Brown and Baass in Quebec [5] produced a ranking by month of PDO crashes and crashes by level of injury severity, adjusting for volume by utilizing crash rates. Similar to Eisenberg, they found that the winter months had the highest number of PDO crashes but much lower rates of injury and the lowest amount of fatalities. A larger Canadian study [6] looked at relative risk of collision and injury during snowfall for six different cities, finding highly variable results. Risk of collision increased from 20% to 80% but risk of injury ranged from -6% to 245%. However, the city with the most snowfall (Quebec City) had the lowest increase of collisions and a negative rate for injury crashes in snow, indicating familiarity. On rural freeways in Iowa (US) Knapp found an overall crash rate during the winter of 0.41 per million km driven during clear days and 5.86 on days where snowfall intensity exceeded 0.5 cm/hr, an increase of over 20 times [7]. Another second study showed a curious finding that total event snowfall decreased crash frequency as drivers stayed away from the freeway as the storms got worse [8]. Qiu and Nixon showed that crashes due to snow were found to be more frequent in the UK than in Canada or the US, although the opposite was the case in rain [9]. Additionally, while there were no improvements over 30 years in crash rates with rain, crash rates with snow did decrease indicating technological improvements. Perhaps most relevant to this paper, Andersson performed an examination of crashes in UK and predicted a drop in winter crashes based upon future climate changes [10]. It is important to note that there have been no previous studies on traffic safety in the United States that have examined freeways with snow totals similar to I-80 in Donner Pass, and very few that also include the effects of climate change similar to Andersson.

Independent of transportation, climate change effects in California have been well documented. Mote [11] showed that the snow-water equivalent (SWE) in California has decreased over 2% for all stations between 1945 and 1995, although this is significantly better than predicted by the hydrologic model. The decrease is more significant at lower altitudes, which Mote successfully correlated with increased temperature. Although up to 1/3 of the changes in temperature and precipitation could be as a result of decadal cycles of the ocean, he showed that the remaining trend in temperature could only be attributed to climate change. Hamlet [12] confirmed SWE decreases of up to 0.1% per year from 1915 to 2003, and noted the peak snow depth has trended earlier in the year. These findings were confirmed by Knowles [13] in 2006, who stratified the results by period of decadal ocean cycles. Perhaps more specific, Pierce [14] broke up California into two parts, the higher southern mountains and the lower but historically wetter northern mountains. Since 1950, these two regions have had differing trends, with the south achieving a higher SWE and north getting a lower one, with the trends much stronger than expected due to climate change. Abatzoglou [15] was able to attribute some of these hidden effects to a phenomenon known as the Pacific North American Teleconnection (PNA). When the PNA stays positive, which it has more often in recent years, temperatures warm and snow rates decrease within California.

Most importantly, Cayan [16] outlined the current climate change predictions for California. Cayan focused on two projections by the Fourth Intergovernmental Panel on Climate Change (IPCC), the B1 low emission projection and A2 medium-high projection. B1 show an increase in carbon release until approximately 2050 and then a decline back to 2000 levels by 2100. In contrast, the A2 projection presumes there is no significant effort in reducing carbon release through the end of the century. Within the study area of Donner Pass, the findings were that by middle of the century (2035-2064) temperatures in Northern California would increase 1.3 degrees C under B1 and 2.25 degrees under A2. In the 2070-2099 period A2 would increase 2.85 degrees, with B1 only 2 degrees. At that time point, snow would disappear entirely below 1000 meters. However, while all models show an increase in temperatures, there is ambiguity in terms of precipitation amounts. With climate change, wetter climates will get wetter while drier climates will get drier. California is uniquely caught between these two effects, and for the purposes of this paper the expectation is that overall precipitation will not change while snow will change to rain.

2.2 Study Area

Donner Pass is a 2100 meter low point in the Sierra Nevada Mountains approximately 280 km to the northeast of San Francisco. The pass is notoriously named after the Donner Party, a large group of travelers attempting to cross the pass in 1846 that was impacted by heavy snow with 40% of the group dying and survivors resorting to cannibalism. Donner Pass is home to the First Transcontinental Railroad (1868) as well as the first transcontinental road (1918), with the freeway (I-80) completed in 1964. Within the pass, 50 km of the I-80 freeway is above 1800 meters in elevation. This section of freeway, the subject of this paper, is among the snowiest sections of freeway in the world and is kept open 365 days per year with very few closures. Average daily traffic ranges from 25000 to 30000 vehicles per day with very high truck percentages, sometimes as high as 20%. To mitigate safety concerns, protect against liability, and to maintain water quality, the California Department of Transportation (Caltrans) enforces strict rules for the use of tire chains as opposed to relying on chemical treatment. When chain control is declared over a certain segment of I-80, the speed limit is set to 50 km/h and mobile check points are positioned at the entrance to the controlled segment to check for chains.

Climate in California is classified as Mediterranean with cool wet winters and hot dry summers similar to the Pyrenees. Most snow falls over 1500 meters, and at 1800 meters almost all of the annual precipitation has fallen exclusively as snow. On average, the Donner Pass receives approximately 950 cm per year of snow. However, the amount of snow is highly variable and is heavily dependent on storm track, the El Nino-Southern Oscillation (ENSO) and the PNA. ENSO refers to the ocean temperature of the equatorial waters off of the coast of South America. PNA is a description of the mid-latitude jet stream and high pressure locations, also affected by ENSO. In the past 50 years, snow totals in Donner Pass have varied from a low of 460 cm in the 1976-1977 winter season to a high of 1700 cm during the 1982-1983 winter season. In years with a very strong ENSO or a highly negative PNA, the storm track can carry a series of storms off of the ocean which can result in 250 cm within one week and sometimes within one storm. As recently as March 2011, 500 cm fell within 25 days. Although the ENSO was not strong in this period, there was a continuous stretch of very low PNA values.

3. RESEARCH APPROACH

3.1 Data Collection and Definitions

This paper focuses on the effect of snowfall and climate change on incidents and crashes. As such, data collected for this analysis included incident, crash, and traffic flow information from Caltrans through the Performance Measurement System (PeMS) interface and accurate snow records from the Central Sierra Snow Laboratory (CSSL). The CSSL is a research lab of the University of California located within the Donner Pass that has recorded snowfall since 1958 and has also recorded the percentage of the storm that is rain since 1988.

Incidents excluding crashes may include vehicle spinouts, breakdowns, chain malfunctions, or other hazards such drifting snow on the roadway. More generally, incidents are situations where the police, known as California Highway Patrol (CHP), has to respond. CHP response is to primarily provide protection to the vehicle occupants or other emergency responders. This is of critical importance during heavy snow and limited visibility. For example, on March 24, 2011, which had heavy snows (38cm), on the 50 km stretch above 1800 meters in the eastbound direction, CHP responded to 16 incidents. These responses included two vehicle spinouts requiring tow service, four disabled vehicles, three additional disabled vehicles that were traffic hazards because of shoulder concerns or had exited the roadway, six traffic hazards that did not involve a vehicle, and one crash between two cars.

The procedure for obtaining incident and crash rates required the use of annual average daily traffic rates (AADT) which were readily available electronically PeMS. It is well understood that traffic volumes can decrease in snow; Datla and Sharma have estimated up to a 1% decrease per centimeter of snowfall [17]. For this experiment, daily volumes were taken directly from detectors located in Colfax, California located 50 km to the west of the study area at an elevation of 700m. Volumes were adjusted between Colfax and the study area by using the AADT values, but in most years the AADT in Colfax was the same as in the study area. By utilizing a detector at 700m, problems due to snow on the detector were avoided.

3.2 Study Design

As shown in the literature review, changes in snowfall due to climate change will be largely due to increased temperature not decreased precipitation. Increases in temperature will result in decreasing snow/water ratios and consequently less snow and more rain. To model the change in snow/water ratio, for each category of snowstorm (0-10cm, 10-25cm, 25-50cm, 50cm+) a linear regression was performed between the low temperature of that particular day and the median of the snow/water ratios for all storms with that low temperature. New snow/water ratios can be found by raising the low temperature from the climate change models. To approximate the amount of new rain, a polynomial regression between low temperature and percentage rain was run for storms with less than 10cm of snow. An increase in low temperature will result in an increase in percentage of rain from the precipitation of these storms. An assumption is that the increase in percentage of rain will approximate the increase in the days of rain as well. It was found that for storms with over 10cm of snow rain was very rare.

With regression equations, the relationship between snow ratio per degree Celsius was found. This relationship was applied to the existing data bank of snowstorms from 1988-2013 and resulted in storms of lesser quantity and increased rain. Storms currently in one existing category, such as snowfall of 25-50cm, would perhaps fall to the lower category of 10-25cm as the snow/water ratio increased. This in turn will have implications for incidents and crashes.

4. FINDINGS

4.1 Snowfall

Table 1 shows the results of daily snow data analysis from the past 25 years (1987-1988 season to present day, 1993 removed for errors). Days between November 1 and May 31 of each winter season were examined. The "Total Rainfall" category is the total rain that fell, including weather events with rain only and weather events that had both rain and snow as a portion of the storm.

Table 1 - Snow Characteristics 1987-2013

	Snowfall (cm)	Days of Snow	Water Equivalent (cm)	Total Rainfall		Rain Only	
				cm total	# days	cm total	# days
Average	928.6	70	97.7	34.7	29	13.1	13
Standard Deviation	286.1	18	34.4	24.6	9	20.5	7

The results strongly support the qualitative description of the climate in this region. Between November 1 and May 31 the Donner Pass area of California will experience 70 days of snow, 29 of them with some rain mixed in and an additional 13 of rain only. The snow totals are highly variable with range of 650 to 1200 cm falling within one standard deviation of the average. Dividing 928 by 70, it is revealed that the average storm produces over 13 cm per storm, consistent with Western United States values, but fairly high as compared to snowy climates in Japan. Aomori, the snowiest city in Japan, reports 774 cm over 107 days, or only 7.2 cm per storm [18]. The ratio of snow to water equivalent, approximately 9.5:1, is also consistent with other locations that are near the ocean and receive generally wet snow. Table 2 breaks down the snowfall into categories by number and severity of the storms. Note, although the previous total noted an average of 70 days with snow, 7 of them are considered days of trace amount and do not contribute to future calculations.

Table 2 – Snowfall by Storm Category

	Snowfall (cm)	Storms 0-10cm		Storms 10-25cm		Storms 25-50cm		Storms 50cm+	
		cm total	# days	cm total	# days	cm total	# days	cm total	# days
Average Snow	928.5	136.8	34.2	263.4	15.8	357.7	10.2	170.6	2.6
Standard Deviation	286.1	49.4	10.8	82.7	5.2	154.5	4.3	104.0	1.6

Although small events constitute the majority of the total number of storms, the majority of the snow accumulation total is within storms from 10cm to 50cm in magnitude. This is of significant importance because in terms of crash severity and visibility, the more snow from stronger storms, the higher costs for maintenance and incident response.

Additionally even in a remarkably dry year, perhaps one full standard deviation below the average, there will still be 11 storms of 10-25cm and 7 of 25cm or more.

4.2 Incidents

The second component of the historical examination was an analysis of incidents, of which crashes are a subset. As discussed in the literature review, it has been revealed by many different researchers that snowfall is directly correlated with a much higher number of incidents and crashes. This study area presents a particularly unique situation as compared to previous studies. Not only are rates of snowfall extreme compared to most study sites in the US and Canada, but conditions specific to this area remove many confounding effects other than the snow. For example, the strictly enforced 50 km/h speed limit keeps speeds reduced, and is self-enforced by vehicles with chains on. Above 50 km/h, chains can dislodge from wheels damaging tires and axles very rapidly. Second, the chains themselves improve traction control. Third, because the incidence of rain is very low and chemical treatment is reduced, the road surface is rarely as icy as one would find in the Eastern US or Europe. The surface can be described in a binary way; either clear for safe driving or covered in snow requiring chain control.

The report of incident and crash data is in two tables; absolute numbers and crash rates. Obviously, the absolute numbers do not control for traffic volumes, which have been shown to decrease during snowfall. The following table shows the results of the incident analysis in absolute terms for the last 10 years, with an incident equating to a CHP response as discussed previously. The number of days for each type of storm in the past 10 years was similar to the 25 year snow analysis shown above.

Table 3 – CHP Incidents by Storm Category

	Clear	Rain	0-5cm Snow	5-10cm Snow	10-25cm Snow	25-50cm Snow	50+ cm Snow
Average	2.1	2.4	4.6	7.2	10.0	16.8	23.6
Standard Deviation	0.49	1.17	1.34	2.08	1.91	4.45	10.16
Total Incidents Per Season	275	31	100	76	163	181	64
% of Season	31%	4%	11%	9%	18%	20%	7%

Without even accounting for differences in daily traffic, there are extreme increases in the rates of incidents as the snowfall increases. A storm day of 25-50cm will likely have 8 times the number of incidents and CHP responses than the reference winter clear day. Note that in terms of incidents, a rainy day was not significantly more than a clear day. This is because there are certain types of incidents that are exclusively seen in snowstorms, notably the spinout and vehicles on the side of the road with chain problems. There was a very high standard deviation for the rate of incidents in the most severe category, storms over 50cm. It is possible that this result is highly variable because of road closures. Although the road is rarely closed the largest storms are most likely to produce a closure.

The following table shows the number of crashes only, as opposed to incidents. Crashes are defined as collisions between multiple cars or between a single car and an object that results in property damage or an injury.

Table 4 – Crashes by Storm Category

	Clear	Rain	0-5cm Snow	5-10cm Snow	10-25cm Snow	25-50cm Snow	50+ cm Snow
Average	0.5	0.8	1.5	2.1	3.0	4.2	5.0
Standard Deviation	0.10	0.52	0.53	0.75	0.74	1.87	5.68
Total Incidents Per Season	62	11	33	22	48	45	14
% of Season	26	5	14	10	20	19	6

Similar to incident table, the number of crashes grew rapidly with the increase of snowfall per day. There was a steady increase of nearly one crash as one moved up each category, topping out at 5 in the highest 50cm category. However, in contrast to the incident table, the rainfall value was more than two standard deviations above a clear day, indicating some significance. Both values were still under one crash per day, and the value for rain was still half of the crash amount for any amount of snow. A key takeaway from these two tables is that the 25-50cm storms are the worst typical storms in terms of incident and crash response. The 50cm+ storms are rare unique events, with some years having zero days. The 25-50cm storms occur on average at least 10 times per year and sometimes more in a strong ENSO or PNA negative year. These storms produce virtually as many crashes and more incident responses than the 10-25cm storms even though the weaker storms occur much more often.

As stated in the study design, the raw incident and crash results can often skew reality as they do not incorporate traffic flow data that reflect changes when snow falls. It was found that daily traffic flow decreases over 30% between a clear winter day and a day with over 25cm of snow. Flows were even lower as the snow totals increased, although the sample size became increasingly small. Nevertheless, the incident and crash results from the tables above were converted to incident and crash rates which are shown in the two tables below. These rates are expressed in events per million kilometers driven. Table 5 is the CHP incident rate and Table 6 is the traditional crash rate.

Table 5 – Incident Rate (million km)

	November	December	January	February	March	April	May	Average
Clear	1.8	2.7	1.9	3.1	2.3	2.1	2.1	2.3
Light 0-10cm	9.4	9.9	5.4	5.5	6.7	4.2	4.6	6.3
Medium 10-25cm	22.8	15.4	12.0	12.5	9.7	8.9	23.6	13.6
Heavy 25+ cm	38.3	20.1	14.3	18.9	22.2	20.7	15.0	20.3

Table 6 – Crash Rate (million km)

	November	December	January	February	March	April	May	Average
Clear	0.34	0.78	0.53	0.51	0.48	0.40	0.30	0.47
Light 0-10cm	2.3	1.9	1.0	1.2	1.6	1.7	2.0	1.6
Medium 10-25cm	5.7	4.8	2.5	3.3	1.9	3.5	8.8	3.7
Heavy 25cm+	5.0	3.1	3.8	3.5	4.7	5.8	5.0	4.0

The values for clear days are similar to those found on other freeways in the United States, and also consistent with the literature the crash rate for clear days was the highest in December when the daylight is the shortest. In light snow, November and December were the worst months which are also consistent with previous work. However, once the snow exceeded 10cm per day, there was a pronounced U-shaped effect which indicated high rates of incidents and crashes at the beginning and end of the winter season with lower rates in the middle of the winter, as shown in the figure below.

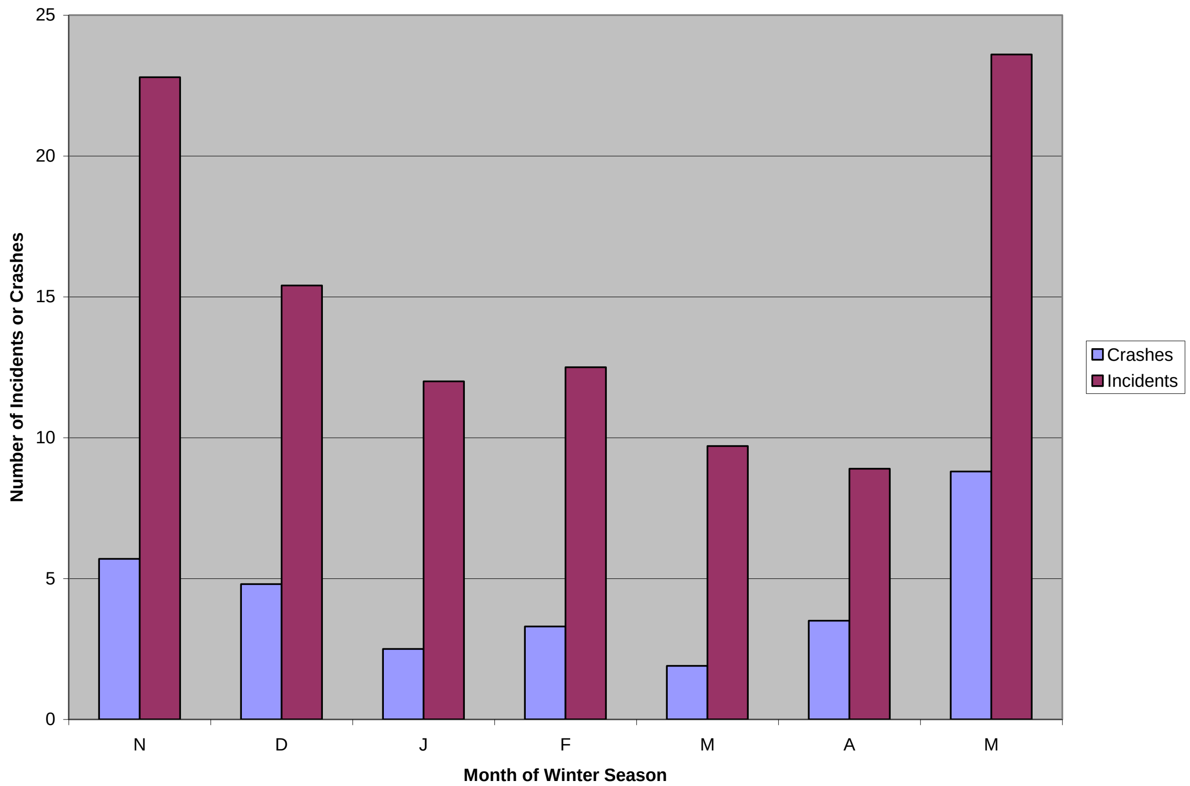

Figure 1 – Crashes and Incidents by Month, Storms 10-25cm

4.3 Changes in Snow to Water Ratios

The linear regressions performed relating the low temperature of the storm and the overall storm snow / water ratio were surprisingly effective. The following table shows the average low temperature, average water equivalent per storm, average storm snow / water ratio, and linear regression equation. As an example, the regression from the 10-25cm is shown in graphical form.

Table 7 – Linear Regression of Snow to Water Ratios

Storm Type	Average Water Equivalent (mm)	Average Low Temperature (x)	Average Snow-Water Ratio (y)	Regression Equation	R-Squared
0-10cm	11.7	-5.3	8.6	-0.52x+3.2	0.74
10-25cm	21.5	-5.9	13.6	-0.64x+5.7	0.71
25-50cm	37.1	-6.0	12.8	-0.72x+6.6	0.78
50+cm	53.7	-7.2	15.9	-1.15x+6.6	0.58

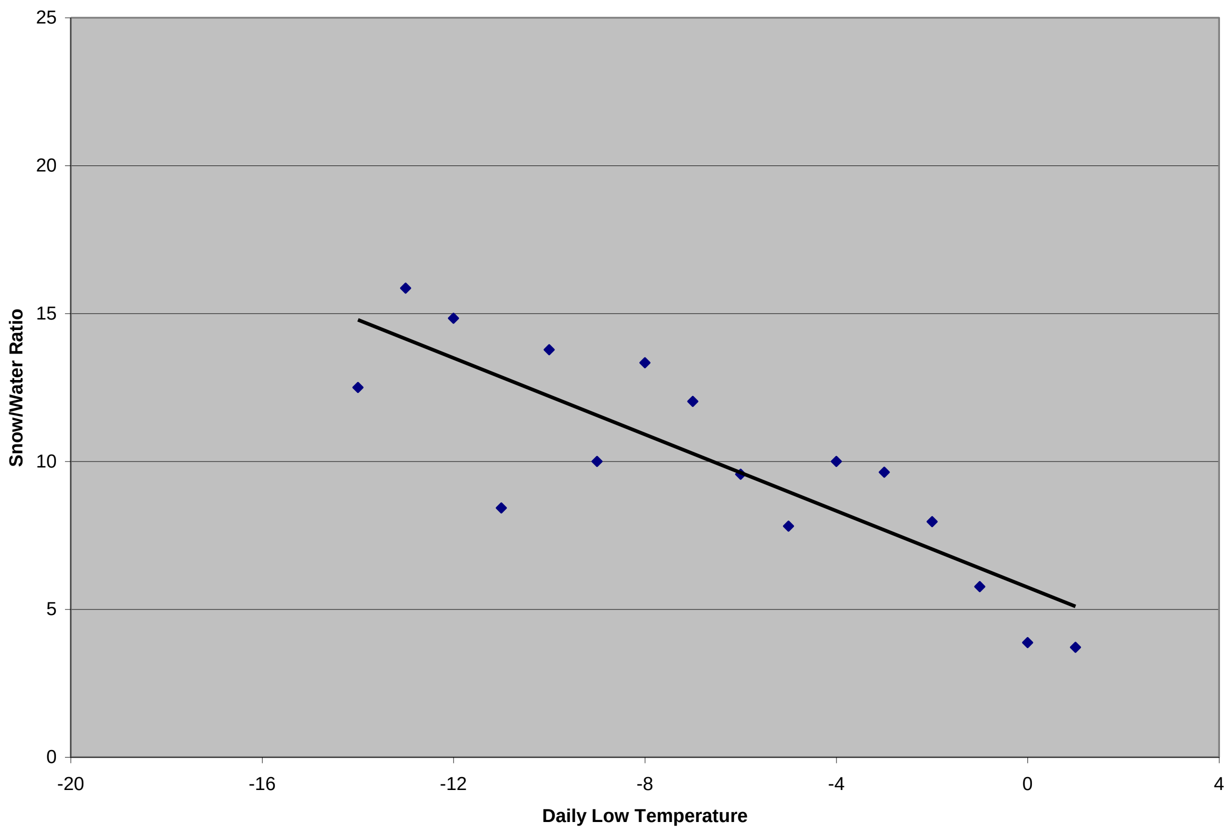

Figure 2 – Linear Regression of Storms 10-25cm

4.4 Effects of decreased snow water ratio on future years

The following table, utilizing the regression equations above, compares the difference in snowfall, CHP responses to incidents and crashes between the existing normal year and a future year with the temperature raised 1 degree Celsius.

Table 8 – Comparison of Historic Storms and With Temperature Raised +1C

	Rain	0-10cm Storm	10-25cm Storm	25-50cm Storm	50cm+ Storm	Totals
Average Per Storm Historic (cm)	-	4.00	16.63	35.01	63.66	-
Number of Days Historic	13.4	34.2	15.8	10.2	2.7	76.3
Snow Historic (cm)	-	136.8	263.4	357.7	170.6	928.5
Incidents Historic	32.2	215.2	215.1	207.1	54.4	724.3
Crashes Historic	10.7	54.7	58.6	40.8	10.7	175.5
Average Per Storm (cm) +1 C	-	3.85	16.39	34.41	63.00	-
Number of Days +1 C	15.8	33.0	15.5	10.0	2.0	76.3
Snow (cm) +1 C		127.0	254.3	342.8	128.5	852.7 -8.2%
Incidents +1 C	37.8	207.7	211.1	202.2	41.4	700.2 -3.4%
Crashes +1 C	12.6	52.8	57.4	39.8	8.2	170.7 -2.7%

The one degree increase in low temperature resulted in both an 8.2% decrease in snowfall and an approximate 3% decrease in crashes and CHP incident responses. This translates to a decrease of 5 crashes and 24 CHP incidents. As one can see in the chart in the second row, the number of 50cm+ storms decreases, but the number of days of the middle two types of storms (10-25cm, 25-50cm) does not decrease all that much as the quantity being lost to the lower category is made up by storms entering from the upper category. In the bin of lightest snowfall, some storms have moved completely from snow to rain. The increases in rainy days stabilize the incident and crash amounts, although as shown in previous tables the rate of incidents and crashes is much lower in rain as opposed to even light snow.

4.4 Climate Change Scenarios

The following three tables show the results of the two primary climate change scenarios, A2 and B1. Utilizing the temperature values from Cayan, A2 and B1 scenario for the midcentury are shown, with the worst case, A2 by 2100, also presented.

Table 9 – Predictions of Future Storms by Climate Change Scenario

	Rain	0-10cm Storm	10-25cm Storm	25-50cm Storm	50cm+ Storm	Totals
Average Per Storm (cm) 2050 B1		3.75	16.28	34.21	62.17	
Number of Days 2050 B1	16.4	32.4	15.9	9.6	1.9	76.2
Snow (cm) 2050 B1		121.6	259.2	329.8	119.4	830.0 -10.7%
Incidents 2050 B1	39.3	204.2	216.5	195.7	39.0	694.5 -4.1%
Crashes 2050 B1	13.1	51.9	58.9	38.6	7.7	170.0 -3.1%
Average Per Storm (cm) 2050 A2		3.68	16.57	34.08	60.85	
Number of Days 2050 A2	19.1	31.4	15.6	8.8	1.4	76.3
Snow (cm) 2050 A2		115.6	257.9	301.2	82.8	757.4 -18.4%
Incidents 2050 A2	46.0	197.5	211.6	179.5	27.6	662.1 -8.6%
Crashes 2050 A2	15.3	50.2	57.6	35.4	5.4	163.8 -6.6%
Average Per Storm (cm) 2100 A2		3.61	16.56	34.08	62.23	
Number of Days 2100 A2	21.1	30.2	15.4	8.6	0.9	76.2
Snow (cm) 2100 A2		109.0	255.8	291.7	54.8	711.2 -23.5%
Incidents 2100 A2	50.7	190.4	210.0	173.8	17.9	642.7 -11.3%
Crashes 2100 A2	16.9	48.4	57.3	34.2	3.5	160.2 -8.8%

With the worst case scenario (A2 in the year 2100), snowfall has decreased over 23%, with CHP incident responses falling 11% and crashes falling 9%. Again, with the assumption of maintaining overall precipitation the decrease in storms is somewhat offset by the increase in rainy days.

5. DISCUSSION

The significant differences by month and by severity (i.e. incident responses vs. crashes) were perhaps higher than expected. The U-shape of the CHP incident response for medium snowstorms (10-25cm) might indicate perhaps a familiarity or surprise effect; drivers are not accustomed to heavy snow in November or May and may not slow down or drive as defensively as they would do in January or February. Caltrans may also be more reluctant to apply chain control. It is noted that this effect is less pronounced in light snow, with December having the highest monthly response rate, but prevalent in the heaviest storms (25cm+), although the spring U-shape peaks in March-April rather than May. Examining the crash rate table, the U-shape was still seen but not to same magnitudes of differences between the average and the maximum month. On clear days, the month December was the worst for crashes, which is consistent with prior literature as December has the least amount of daylight. The small difference in crashes from the medium storms to the heavy storms would perhaps indicate that above a certain level of snowfall, drivers become more experienced, but this stands in contrast in the number of CHP incident responses. This definitely decreased the potential positive safety benefits of the climate change scenarios. The overall conclusion from this part of analysis is that heavy amounts of snow can cause significant increases in both the rate of CHP incident responses and crashes.

The changes in crash amounts from the climate change scenarios were perhaps less than expected, even as the reductions in snow exceeded 10%. The 2050 B1 scenario only resulted in the reduction of five crashes and 30 incident responses. Even if we conservatively estimate each crash to be worth $50000 USD, the savings is small. Crashes with severe injury or death are extremely rare in snowfall in California because of the strict enforcement of chains and low speeds. For example, in 2011, a year of very high snowfall there was only one fatal accident on I-80 during snowfall the entire year, although there were two that involved rain. The larger decrease of course was in terms of CHP incident responses. Certainly with fewer storms there will be fewer spinouts and disabled vehicles, but the primary economic entity that will be affected will be tow service as there will be fewer vehicles to pull out of the snow. In a more macroscopic way, the entire winter sports industry could decline due to lack of snow which would lower volumes and in turn lower both crashes and incidents even further.

The primary technique for this analysis was to compare the snow/water ratio to low temperature by day; temperatures go up, snow ratios go down, less snow falls, fewer crashes. The rationale for choosing the low temperature is that it is more likely to be when the most snow falls as temperatures in California tend to drop as the storm passes over the study area. Following the assumption that the storms themselves will not differ in track and intensity from those over the past 25 years could be overly simplistic. This assumption appears to be true, but climate change in the future may bring changes unforeseen. For example, the days with precipitation could increase but the quantity could decrease which would further decrease the crashes and incidents as it would eliminate the largest storms. However, if the opposite were to be the case (fewer storms but larger storms), there may not be any measurable decrease or improvement for traffic safety. Perhaps most importantly, the selection of the categories relating to the size for the storm created a discrete picture. Depending on the intensity of the snowfall, a 12cm storm and a 22cm storm could be very different in nature as the 12cm storm could occur entirely at night if it were intense enough. A more continuous function could prove to be beneficial, although this would have effects on the regression effort.

Future research might focus on severity of crashes as well as the day of week or day of storm effect. It has been shown that when there are long intervals between snow events, the first day of the storm tends to perform very poorly in terms of traffic safety, but following days are much better. Additionally, during the winter season traffic volumes can be higher on Fridays and Sundays. This analysis agglomerated volumes by severity of storm, not day of week.

Lastly, this report did not examine costs from winter maintenance. For Caltrans there will be significant savings as the amount of snow decreases. Furthermore, the increased number of rainstorms will have the added effect of cleaning lightly covered snowy areas. With the overall snow elevation increasing, maintenance depots at lower elevations could be closed and crews could be dispatched to other areas. The I-80 winter effort currently is staffed by approximately 500-600 employees who work in shifts through the day and night. Through innovative technologies, Caltrans reduced its budget from 6 million USD in 1990 to just 2.5 million USD by 2001 [19]. This number would hopefully be further reduced and would allow monies to be transferred to other infrastructure projects.

6. CONCLUSIONS

Over 60 days of snowfall affect a 50km section of I-80 freeway near Donner Pass, California. It was found that about half of the storms are 10cm or less, with the remaining storms increasing in severity up to approximately three storms of 50cm or more per year. CHP incident responses increased dramatically during periods of heavier snow, while the crash rates increased at a more moderate rate. Utilizing a simple regression technique comparing temperatures to snow/water ratios, future temperature changes from well established climate change scenarios were applied to the existing profile. The models predicted decrease quantities of snow ranging from 10-20%, but with steady overall precipitation the increased amount of rain nullified much of the safety benefits from less snowfall. Nevertheless, in the more severe climate change warming scenario CHP incidents would decline over 10% and crashes would decrease 8% by 2100. This equates to a drop of 80 incidents and 15 crashes.

The Western United States perhaps more than any industrialized region, relies on annual snowpack for drinking water and agricultural irrigation. These same snowfalls can create traffic nightmares for vehicles in the winter in terms of both speed and safety. Climate change will certainly affect high altitude roadways in California, particularly I-80.

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