The Effects of Rain on Freeway Traffic in Southern California

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ABSTRACT

A number of studies in the past have quantified the impact of rain on traffic parameters but all of them were limited to wet areas. The research reported in this paper have expanded the literature by studying the impact of rain in a dry area such as Southern California, and investigating for regional differences in the impact. Traffic data (loop detectors) and precipitation data (rain gauges) from Los Angeles Metropolitan Area has been analyzed to access the impact of rain on traffic stream parameters such as free-flow speed, the speed at capacity, and capacity. Rainfall events have been categorized as light, medium, and heavy as discussed in Highway Capacity Manual (HCM) 2010. Density plots and fundamental diagrams for different rain types proved that free-flow speed, speed at capacity and capacity are reduced by 5.7%, 6.91%, and 8.65% respectively for light rain, 11.71%, 12.34%, and 17.4% respectively for medium rain, and 10.22%, 11.85%, and 15.34% respectively for heavy rain. The reductions for free-flow speed are lower, whereas, for speed at capacity and capacity are higher than those reported in HCM 2010. Moreover, the headway is increased during rain that exhibits cautious driving behavior. Multiplicative weather adjustment factors have been computed to compensate the loss of speed and capacity. This paper also demonstrates the spatial and temporal impact of rain on traffic. Downstream traffic is not much affected by a rainfall event while the upstream traffic is negatively impacted. This paper is expected to support weather-responsive traffic management strategies for dry areas.

Keywords: rainfall, dry area, free-flow speed, speed at capacity, capacity, weather-responsive

INTRODUCTION

With an increasing number of automobiles, safety and mobility have become major concerns for professionals responsible for design and operation of freeway facilities. Along with other factors responsible for congestion, adverse weather is an important factor affecting it.

Many studies have proved that rain certainly has a negative impact on freeway capacity and operating speeds *(e.g.1-10)*. Lamm et al. *(1)* concluded that effect of light rain is negligible on speeds (and presumably not on capacities) unless there is considerable water visible on the pavement whereas heavy rain is expected to have a noticeable effect on traffic flow due to reduced visibility. Similarly, Ibrahim and Hall *(2)* found minimal reductions in maximum observed flows and operating speeds for light rain but significant reductions for heavy rain. Brilon and Ponzlet *(3)* concluded that reduction in capacity varies based on the number of lanes, light conditions (day/night) and day of the week (weekday/weekend). Based on research *(1-3)*, Highway Capacity Manual (HCM) 2000 *(4)* first addressed the impacts of rain in Chapter 22. However, these studies did not define the intensity range for light and heavy rainfall. Smith et al. *(5)* categorized rain based on intensity levels as light (0.01 - 0.25 inches/hour) and heavy (0.25 inches/hour and greater) and investigated its effect on freeway capacity and operating speeds in Virginia. Maximum Observed Throughput approach was used to estimate the capacities and it was assumed that mean of the highest 5% of flow rate could be used to determine effective capacity. Agarwal et al. *(6)* quantified the impact of rain, snow, and various pavement surface conditions on freeway operational speeds and capacity in the metropolitan region around Twin Cities, Minnesota and found that speed reductions were significantly lower than those specified in HCM 2000. Data having very low occupancy (< 5%) due to a freeway operating below capacity, or very high occupancy (> 50%) due to the breakdown of flow, were eliminated and maximum observed throughput approach was used to estimate capacities of freeways. The results of this study were considered for HCM 2010 *(7)*. Another research by Unrau and Andrey *(8)* modeled the effects of rainfall on freeway operations and observed that speed is reduced during a rainfall event and it is strongly dependent on volume. For uncongested traffic, speed decreases and time gap increases during a rainfall event at night and these changes are even more in the case of rainfall during the daytime. For congested traffic, no significant reduction is noticed in volume or time gap but speed is reduced significantly.

Furthermore, Rakha et al. *(9)* quantified the impact of adverse weather on traffic stream parameters such as free-flow speed, the speed at capacity, capacity, and jam density based on data collected from three different locations in the US. Traffic parameters were estimated using Van-Aerde Model (proposed by Van Aerde and Rakha *(10, 11*) and compared against the base condition of no rain and high visibility to compute the changes. Weather adjustment factors were also computed for various traffic parameters and modeled as a function of precipitation type, precipitation intensity, and visibility level. This research demonstrated that reduction in traffic parameters is affected by the regional variation as the drop in free-flow at two different locations was found to be statistically different. The potential reason for these variations was interpreted to be the awareness of people regarding the dangers in an area during adverse weather condition and their cautious behavior to mitigate them. The paper concluded that traffic stream jam density was not affected by adverse weather conditions. Billot et al. *(12)* used a multilevel approach to study the impact of rain on headway, spacing, platooning, and fundamental diagrams for a French interurban motorway. They followed Rakha et al. and used Van-Aerde Model to estimate key traffic parameters and plot fundamental diagrams. This study suggested that there is a platooning phenomenon during a rainfall event resulting in speeds reduced up to 20%. A summary of results of past studies has been tabulated in Table 1.

TABLE 1 Summary of Past Studies

Source	Location	Rainfall Type	Rainfall Intensity (inch/hour)	Reductions (%) Free-flow speed	Speed at capacity	Capacity
Ibrahim and Hall (1994)	Mississauga, Ontario, Canada	Light	—	1.9	7.9–13.7	Minimal
		Heavy	—	4.8–6.7	14.6–16.8	14–15
Highway Capacity Manual (2000)	—	Light	—	8.3	7.9–13.7	Minimal
		Heavy	—	16.7	14.6–16.8	14–15
Smith et al. (2004)	Hampton, Virginia	Light	0.01-0.25	5–6.5	—	4–10
		Heavy	≥ 0.25	5–6.5	—	25–30
Agarwal et al. (2006)	Minneapolis, Minnesota	Light	≤ 0.1	1–2	—	1–3
		Medium	> 0.1–0.25	2–4	—	5–10
		Heavy	> 0.25	4–7	—	10–17
Unrau and Andrey (2006)	Toronto, Ontario, Canada	Light	0.004–0.1	10	—	—
		Medium	> 0.1–0.25	—	—	—
Rakha et al. (2008)	Seattle, Washington; Minneapolis, Minnesota; Baltimore, Maryland	Light	≤ 0.1	2–3.6	8–10	10–11
		Medium	> 0.1–0.25	—	—	—
		Heavy	> 0.25	6–9	8–14	10–11
Billot et al. (2009)	Paris, France	Light	≤ 0.08	8	—	18.5
		Medium	0.08–0.11	12.6	—	21
Highway Capacity Manual (2010)	—	Light	≤ 0.1	8.3	3.7	1.17–3.43
		Medium	> 0.1–0.25	12	6.5	5.67–10.10
		Heavy	> 0.25	16.7	9.3	10.72–17.67

— = not applicable/not available

As evident from the aforementioned studies, the impact of rain has been explored in areas receiving about 30 inches average annual rainfall or more. Areas receiving less than 20 inches annual precipitation are considered as dry which can be further categorized as arid (less than 14 inches annual precipitation) and semi-arid (less than 20 inches annual precipitation). Southern California receives about 14.93 inches annual precipitation making it a dry area as compared to past study areas. This region is one of the most populous regions in the whole US and hence, there is a need to expand past literature to such region exhibiting dry climatic conditions. Figure 1 shows Average Annual Rainfall and Average Annual Daily Traffic (AADT) in Los Angeles Area compared to previous study areas in the US. It is evident from the figure that traffic volume is almost double and rainfall is almost half as compared to other areas. Unfortunately, no research so far directly addresses the impacts of rain on traffic in a dry and congested area, such as Southern California.

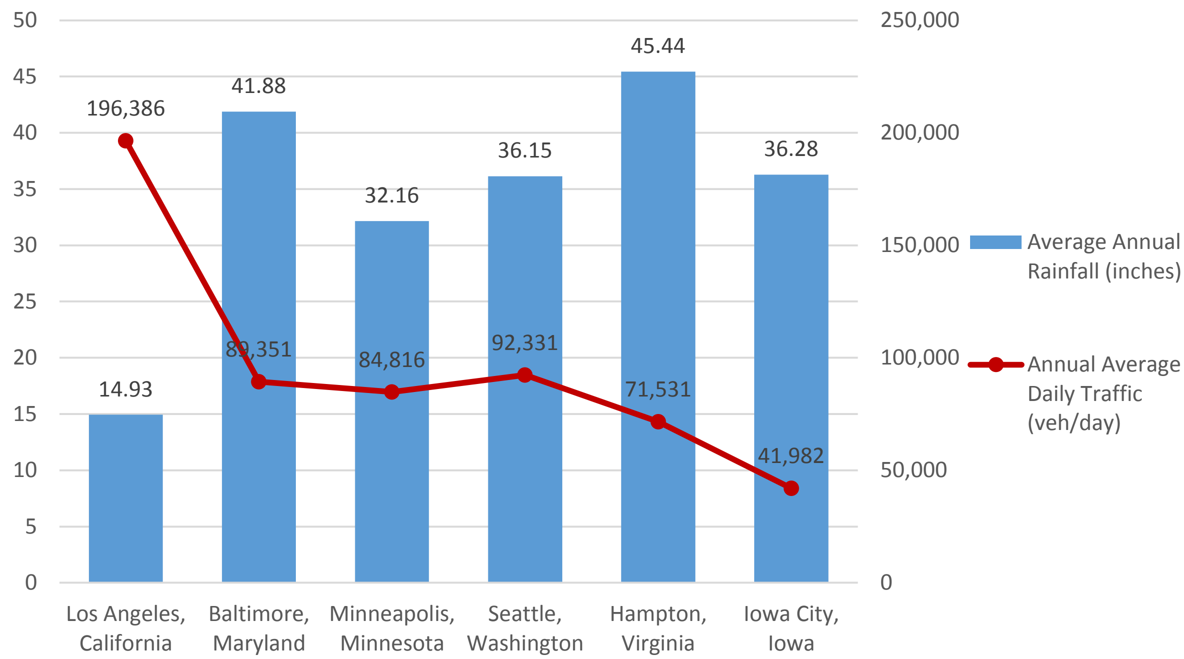


FIGURE 1 Average annual rainfall (30-year average) and Average Annual Daily Traffic (2011) for different study areas.

The primary purpose of this paper is to investigate the impact of rain on traffic in dry areas to see if there are regional differences. Initially, traffic data from major freeways and rainfall data from nearby rain gauges were analyzed using density plots, and changes in flow, average speed, density, and average headway were observed for various rainfall intensity. Then, a software based on non-linear least squares was used for calibration of a traffic model and key traffic parameters were estimated to plot fundamental diagrams for different rainfall intensities. Furthermore, the spatial impact of rain was demonstrated using contour plots of a section of the freeway and comparing the traffic parameters during rain and normal conditions. It has been concluded that reductions in key traffic parameters were different from past studies which prove the existence of regional differences. The significant difference in the observed reduction in speed and highway capacity compared to the HCM 2010 and other studies demonstrate the need for adjustment factors (based on regional differences) in addition to HCM 2010 guidelines on capacity reduction. This research is expected to contribute to better understanding freeway traffic operations and safety during rainfall in dry areas.

This paper is organized as follows: Section 2 introduces the methodology for data collection, followed by data analysis of the impact of rain on traffic parameters, fundamental diagrams, and time-space area in Section 3. Section 4 highlights the significant difference of the observed drop in highway capacity in Southern California compared to HCM 2010 and other studies. Finally, Section 5 concludes this paper with some remarks.

METHODOLOGY

Data Description

Traffic data in California is provided by Caltrans Performance Measurement System (PeMS). Los Angeles County has about 4550 stations deployed throughout the county that record traffic data from about 10,000 loop detectors. For this study, processed 5-min data containing speed, flow, and occupancy, for 7 years (2009-2015) were downloaded from the PeMS website. Only the data collected by mainline detectors were used for this study. The malfunctioning detectors with errors or no data are assigned values imputed based on historical trends and neighboring detectors. To make sure the data collected were accurate, a threshold of the healthy index of 70% was used for 5-minute data considering the age of detectors. That means the data having less than 70% observed values or more than 30% imputed values were discarded.

Weather data were initially obtained from National Climate Data Center (NCDC) that were archived as 1-minute and 5-minute weather data from Automatic Surface Observing Station (ASOS), but these data were unprocessed and hence, not usable. Instead, the study used 15-minute precipitation data provided by the Los Angeles Hydrology Department.

As discussed in HCM 2010, accumulated rainfall amounts were converted into hourly rates (rainfall intensities) and were categorized based on intensities, as light (<0.1 in./h), medium (0.1 to 0.25 in./h), and heavy (> 0.25 in./h) rain. To maintain consistency with rainfall data, 5-minute traffic data were aggregated and converted to 15-minute data.

As past studies suggested *(9,12)*, traffic data were filtered based on certain criteria discussed below:

- Close to weather station: Weather stations near to six major freeways (I-10, I-5, I-210, I-405, I-110, and I-105) were chosen using ArcGIS and a buffer area of the 3-mile radius was used to choose the traffic stations in the proximity of these weather stations.
- Not influenced by lane-changing behavior: Data within 0.25 mile of on/off ramps were removed that might have the influence of the merge, diverge, or weaving and exhibited intensive lane-changing behavior.
- Not influenced by breakdown: Data having very large occupancy (>60%) were removed to ensure that data representing the total breakdown of the facility (e.g. during incidents) were eliminated without removing the data collected during congested conditions.
- All traffic conditions: Traffic data were inspected by plotting fundamental diagrams so that it covered all the traffic conditions: uncongested, at capacity, and congested. Note that only mainline detector data were considered. Other lane types such as HOV, on-ramp, off-ramp, etc. were not considered.

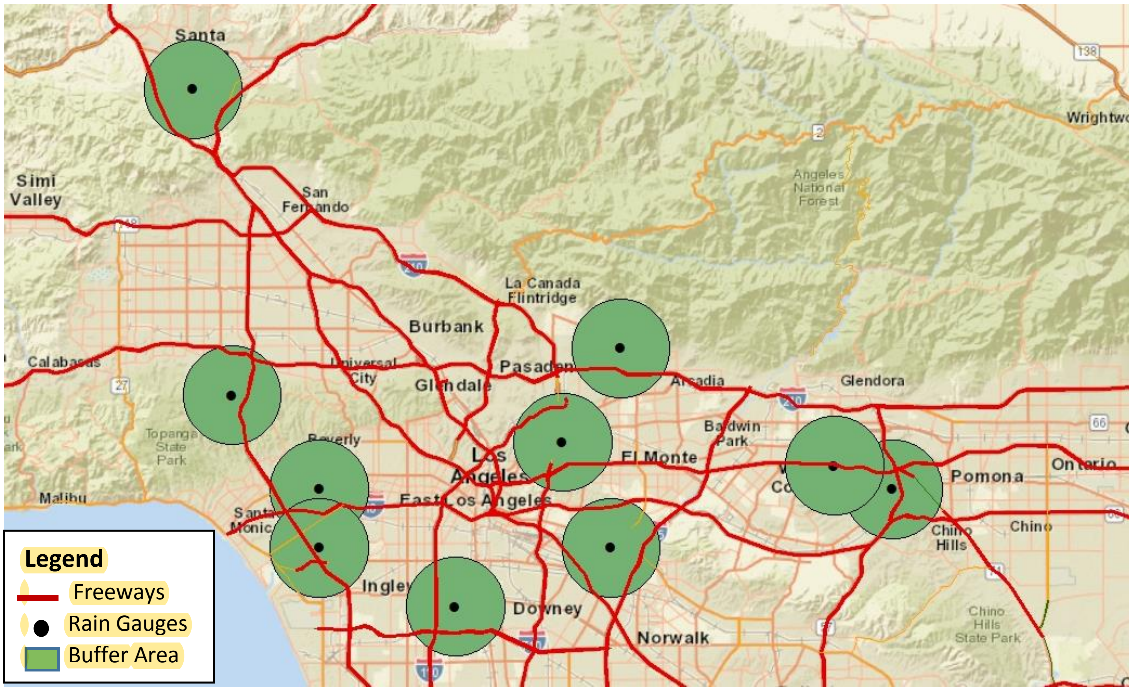


FIGURE 2 Study area (freeways and rain gauges).

Dataset Construction

After basic filtering of rainfall and traffic data, they were merged together and several datasets were constructed based on the following criterion:

- Traffic pattern: Stations with similar traffic patterns were grouped together by visually analyzing fundamental diagrams. In this way, stations adjacent to each other automatically fell into same groups.
- Temporal distribution: Data were then divided into groups based on month and year of occurrence of the rainfall event.
- Rainfall intensity: The data were further categorized as no rain, light rain, medium rain, and heavy rain.
- Coverage: Finally, all intensity groups were screened to choose data sets having at least 60 observations in order to estimate key traffic parameters.

The data groups containing traffic data during a rainfall event were paired with clear weather traffic data one week before and after the rainfall event. In this way, 171 final rainfall datasets (41-light, 110-medium and 20-heavy) were constructed for further analysis.

DATA ANALYSIS

Density Plots

The distribution of traffic data during various rainfall types was examined visually by plotting density plots for flow, speed, density and average headway as shown in Figure 3(a), 3(b), 3(c), and 3(d), respectively. The data used for these plots were modified to represent conditions when a facility is operational (neither much below the capacity nor totally stuck). For this purpose, data with occupancy greater than 0.05 was used to compare the parameters. Also, speed greater than 45 mph was used for visual comparison as speed in this range roughly represents the operational speed of the facility. Most of the density plots appeared to be normally distributed with some skewness. Hence, to compare different distributions, they were fitted using gamma distribution function as it can show skewness due to its dependency on alpha and beta calculated from mean and variance of data. A clear change in the distribution was noticed for flow, speed, and average headway, with a change in rainfall intensity, the only exception being the case of density with very little or no change. This may be related to the fact that both speed and flow have reduced with an increase in rainfall intensity, and density being the ratio of flow to speed have remained more or less the same. All distributions were tested for normality using Shapiro-Wilk Test and Anderson-Darling Test against the null hypothesis that it is normally distributed. All the distributions were found to be non-normal as the p-value for all distributions was less than 0.05 leading to rejection of the null hypothesis. Hence, distributions were tested using non-parametric tests like Mann-Whitney U Test and Kolmogorov-Smirnov Test against the null hypothesis that two samples come from the same population. A p-value less than 0.05 in Mann-Whitney U Test for all the distributions resulted in the acceptance of alternative hypothesis that a population tends to have larger values than the other. Similarly, a p-value less than 0.05 in Kolmogorov-Smirnov Test for all distributions proved that they do not come from same distribution, with an exception in the case of density in heavy rain compared to light rain. Although the normality test suggested that data were not normal, they appeared to be close to a normal distribution. Hence, Analysis of Variance (ANOVA) test was done to get some rough estimate of differences. Using non-normal data for ANOVA may result in false positive results but some studies *(14-16)* suggest that this test is not very sensitive to moderate deviations from normality when the sample size is large. However, some of the parameters such as density, still have a large tail and ANOVA may report over-optimistic results. Results for various tests are summarized in Table 2.

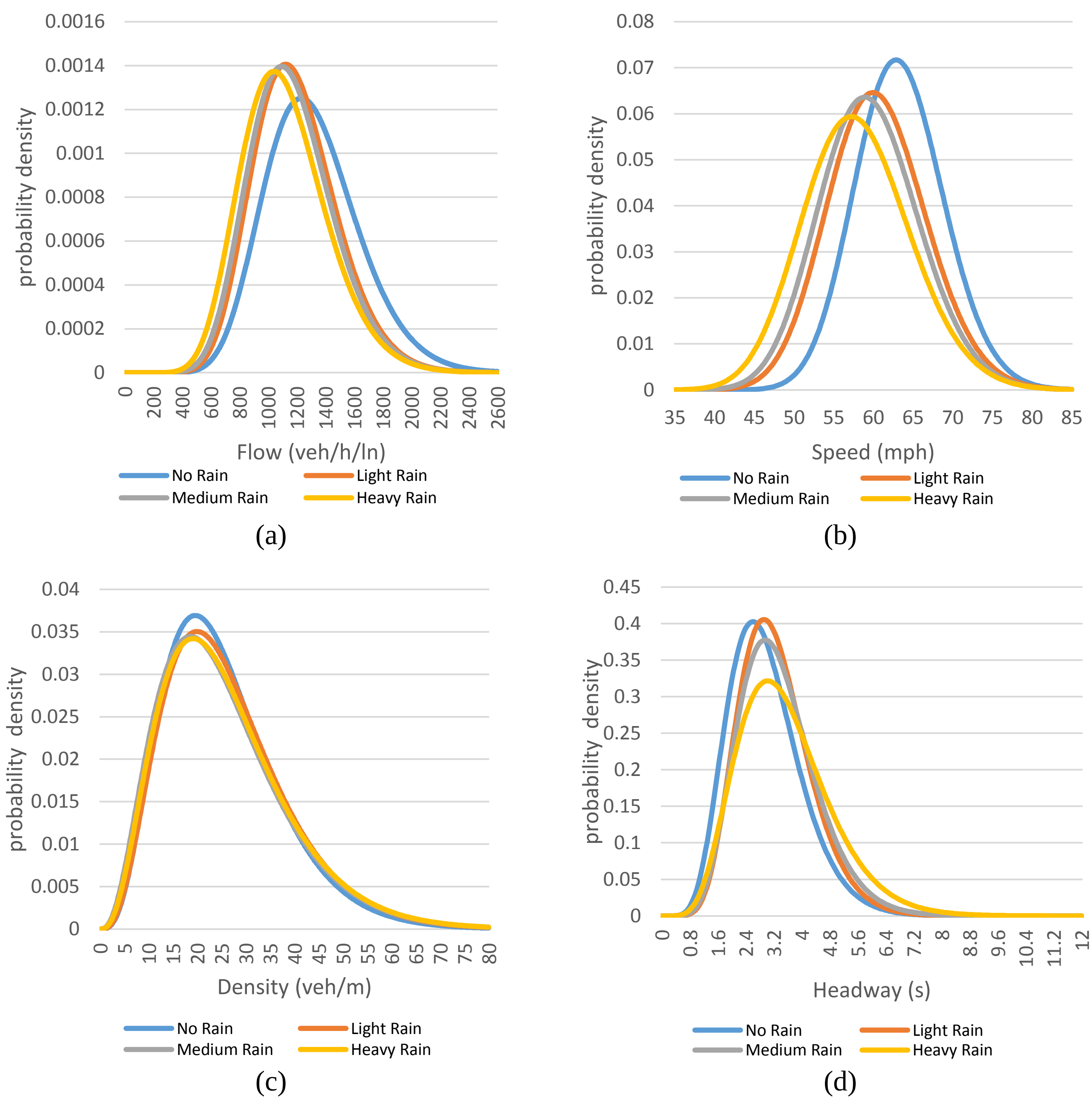


FIGURE 3 Density plots for (a) flow, (b) speed, (c) density, and (d) average headway, for various rainfall types.

TABLE 2 Summary of Density Distribution Functions for Various Rainfall Categories

			Normality Test		Comparison with "No Rain"					
			Shapiro-Wilk Test	Anderson-Darling Test	Kolmogorov-Smirnov Test	Mann-Whitney Test	ANOVA			
Rain Type	Mean	Median	P-Value	P-Value	P-Value	P-Value	Difference	Lower	Upper	Adj P
Flow										
No	1313.3	1329	<0.001	<0.001	—	—	—	—	—	—
Light	1193.6	1205	<0.001	<0.001	<0.001	<0.001	119.67	101.14	138.20	<0.001
Medium	1168.1	1166	<0.001	<0.001	<0.001	<0.001	145.17	134.20	156.13	<0.001
Heavy	1120.9	1132	0.003	0.010	<0.001	<0.001	192.36	167.00	217.72	<0.001
Speed										
No	63.358		<0.001	<0.001	—	—	—	—	—	—
Light	60.586	61.69	<0.001	<0.001	<0.001	<0.001	2.771	2.497	3.046	<0.001
Medium	59.573	59.79	<0.001	<0.001	<0.001	<0.001	3.785	3.607	3.963	<0.001
Heavy	58.009	58.01	<0.001	<0.001	<0.001	<0.001	5.349	4.931	5.766	<0.001
Density										
No	25.280	22.63	<0.001	<0.001	—	—	—	—	—	—
Light	26.140	23.32	<0.001	<0.001	<0.001	0.030	-0.855	-1.575	-0.135	0.012
Medium	25.400	22.14	<0.001	<0.001	<0.001	0.009	-0.123	-0.549	0.303	0.880
Heavy	25.850	22.79	<0.001	<0.001	0.045	0.599	-0.570	-1.556	0.415	0.445
Average headway										
No	2.970	2.708	<0.001	<0.001	—	—	—	—	—	—
Light	3.244	2.987	<0.001	<0.001	<0.001	<0.001	-0.275	-0.337	-0.212	<0.001
Medium	3.326	3.087	<0.001	<0.001	<0.001	<0.001	-0.356	-0.393	-0.319	<0.001
Heavy	3.522	3.180	<0.001	<0.001	<0.001	<0.001	-0.552	-0.638	-0.467	<0.001

— = not applicable

Fundamental diagrams

Speed, flow, and density relationships were explored for different rain categories with the help of fundamental diagrams. There are many single and multiple regime models being developed so far such as Greenshields' Model, Pipes' Model, Greenberg's Model, Newell's Model, etc.*(17)*,*(18)*,*(19)*. Eventually, Van-Aerde Model was chosen for this study as it is a combination of Greenshields and Pipes model with a greater degree of freedom *(17)*. This allows speed at capacity to differ from free flow speed and thus, have a better fit to field data. The calibration of the model depends on three parameters (c1, c2, c3) that are the function of free flow speed (u_f), the speed at capacity (u_c), capacity (q_c) and jam density (k_j). The functional form of Van-Aerde model is formulated as:

$$k = \frac{1}{c_1 + \frac{c_2}{u_f - u} + c_3 u}$$

$$c_1 = \frac{u_f}{k_j {u_c}^2}\left(2u_c - u_f\right)$$

$$c_2 = \frac{u_f}{k_j {u_c}^2}\left(u_f - u_c\right)^2$$

$$c_3 = \frac{1}{q_c} - \frac{u_f}{k_j {u_c}^2}$$

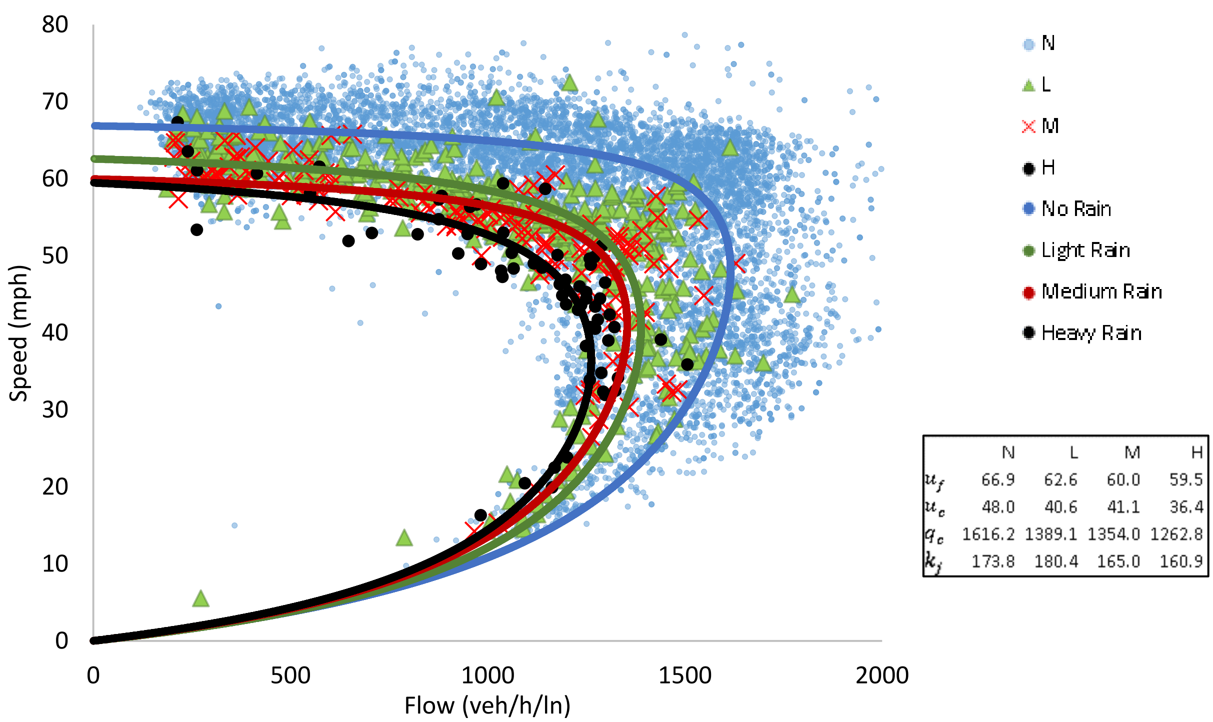
Where, $k \; = \; traffic\ stream\ density\ (vehicles/km),$
$u \; = \; traffic\ stream\ space\text{–}mean\ speed\ (km/h)\ assuming\ that\ all\ vehicles\ are\ traveling\ at\ the\ same\ average\ speed\ (by\ definition\ given\ that\ the\ traffic\ stream\ is\ in\ steady\ state),$
$u_f \; = \; facility\ free - flow\ speed\ (km/h),$
$u_c \; = \; speed\ at\ capacity,$
$c_1 \; = \; fixed\ distance\ headway\ constant\ (km),$
$c_2 \; = \; variable\ headway\ constant\ (km^2/h),$
$c_3 \; = \; variable\ distance\ headway\ constant\ (h),$
$q_c \; = \; facility\ capacity\ (veh/h), and$
$k_j \; = \; facility\ jam\ density\ (veh/km).$

SPD_CAL software developed by Rakha and Van Aerde *(10)* was used to calibrate the model that is based on the non-linear least squares approach in three dimensions. It iterates various values to select parameters that minimize the sum of squared orthogonal errors *(10)*. Also, its efficiency has been validated in the previous study *(9)* by estimating the parameters using low-density and flow data. The results were consistent, with errors not exceeding 1%.

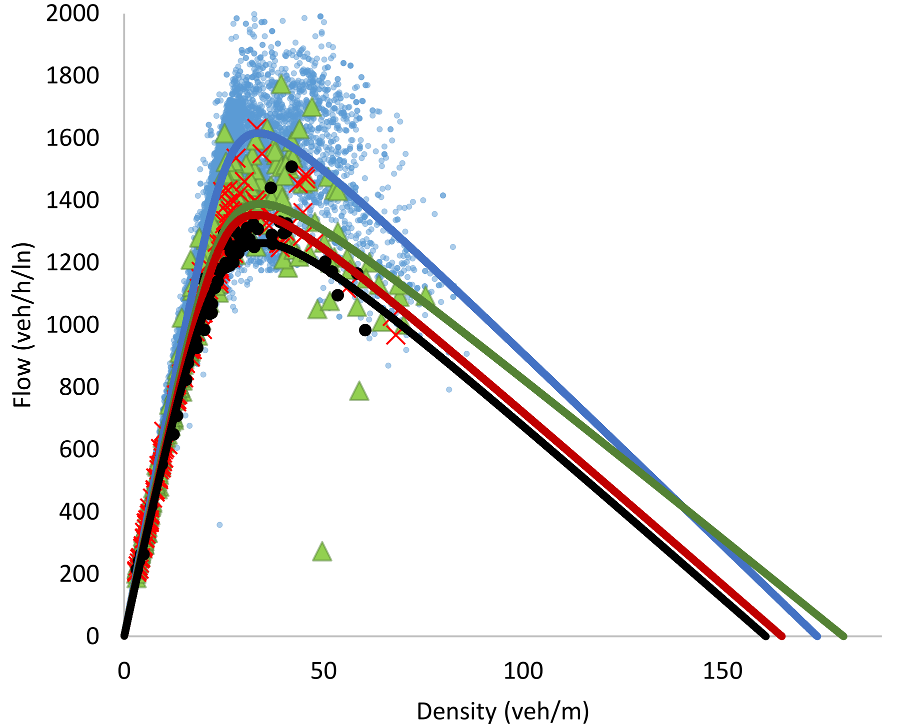
Free-flow speed, the speed at capacity, capacity, and jam density were estimated for all the groups and results were analyzed to quantify the trends and come up with adjustment factors. All the estimates for a certain rain category were compared with estimates for no rain category in the same group to estimate the percent change in parameters. To estimate the adjustment factor, the ratio of the value of estimated key parameter in a certain rainfall category, relative to no rain category, was calculated. It was observed that there was a drop in free-flow speed, the speed at capacity and capacity for most of the groups with some exceptions but no such change in jam density was noticed. Moreover, estimates of jam density were highly variable. The flow-density curve becomes linear in the congested region and passes through the point representing critical density and jam density. The absence of enough data in this region may have projected the flow-density curve to false jam density values. However, a few groups that had enough data in that region showed minor changes in jam density. Previous studies *(9)* suggested that jam density is insensitive to change in weather, however, this partial change may have occurred due to the cautious driving behavior. Some studies *(12)* proved that during rain, spacing between the cars is increased during rainfall events. This behavior might be applicable even in queue formation during rain but this topic is beyond the scope of this study and hence will be explored in a future study. After calculating the percentage drop and adjustment factors for each group, results were aggregated to report overall changes as shown in table 3. Fundamental diagrams for a group can be seen in Figures 4(a), 4(b), and 4(c) that shows a clear change in free flow speed, the speed at capacity and capacity with a change in the rainfall intensity, as expected from the previous analysis of density plots.

TABLE 3 Summary of Key Parameter Changes for Various Rainfall Categories

			% Change in parameter			Weather Adjustment Factor		
Parameter	Rain Type	Number of data sets	Lower Limit	Mean	Upper Limit	Lower Limit	Mean	Upper Limit
free-flow speed	Light	33	-7.16	-5.70	-4.24	0.93	0.94	0.96
	Medium	97	-7.86	-6.91	-5.95	0.92	0.93	0.94
	Heavy	16	-10.29	-8.65	-7.02	0.90	0.91	0.93
speed at capacity	Light	33	-14.90	-11.71	-8.51	0.85	0.88	0.91
	Medium	97	-14.85	-12.34	-9.83	0.85	0.88	0.90
	Heavy	16	-22.98	-17.40	-11.82	0.77	0.83	0.88
capacity	Light	33	-11.62	-10.22	-8.81	0.88	0.90	0.91
	Medium	97	-12.95	-11.85	-10.74	0.87	0.88	0.89
	Heavy	16	-18.39	-15.34	-12.29	0.82	0.85	0.88

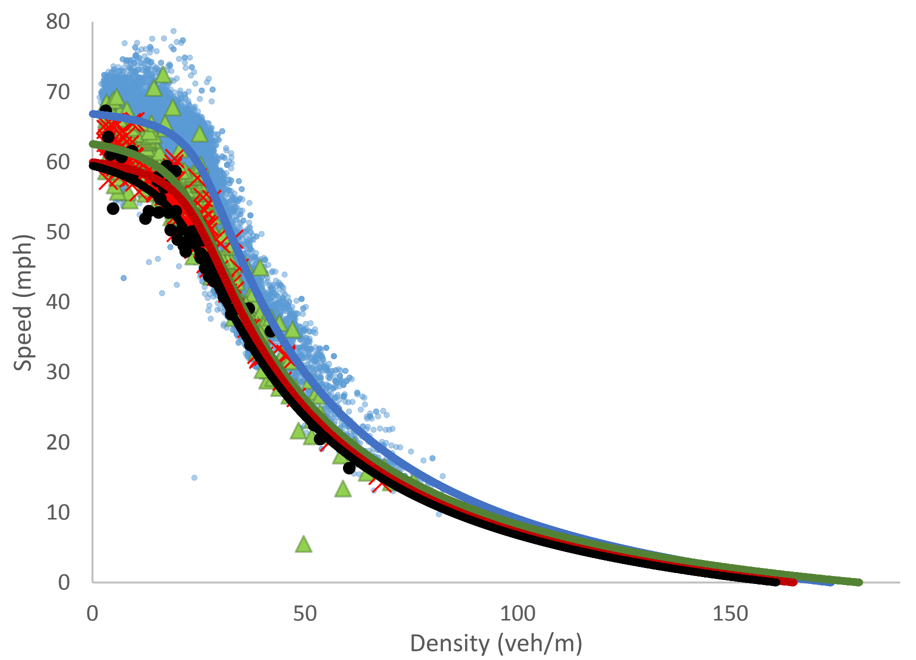


(a)



	N	L	M	H
u_f	66.9	62.6	60.0	59.5
u_c	48.0	40.6	41.1	36.4
q_c	1616.2	1389.1	1354.0	1262.8
k_j	173.8	180.4	165.0	160.9

(b)



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k_j	173.8	180.4	165.0	160.9

(c)

FIGURE 4 Calibrated Fundamental Diagrams for various rainfall categories (December 2010): (a) speed-flow relationship, (b) flow-density relationship, and (c) speed-density relationship.

Spatial and Temporal Impact Zone Analysis

An effort was made to study the spatial and temporal impact of rain on the traffic by visually analyzing changes in the pattern of speed, and flow. Freeway I-10 was chosen for this study after looking at the rain patterns using online archived radar map. Different sections of this freeway received rain for various durations on 5th February, between 2:00 PM and 9:00 PM, and there was no rainfall about a week before and after this rainfall event, which made it a suitable choice to compare the traffic parameters. Contour plots were plotted for speed, and flow for the day it rained and for the same day a week before as shown in Figures 5 and 6. The area with black dots and boundary represents the period of rain that can be compared with the same area a week before the rainfall event. There was a significant drop in speed during rain and a marginal drop in the flow which is evident from the amount of redness in the study area for both days. The spatial and temporal impact of rain can be explained using the following scenarios:

- Scenario A – Spatial (Postmile 18-41, 2:00-6:00 PM): When it was raining over postmile 18-34, downstream section (pm 34-41) was similar to “No Rain” situation (1 week before). This means, there is no impact of rain on downstream traffic.
- Scenario B – Spatial (Postmile 18-38, 6:00-9:00 PM): When it was raining over postmile 25-38, upstream section (pm 18-25) was comparatively redder than “No Rain” situation (1 week before). This confirms that rain has an impact on upstream traffic.
- Scenario C – Temporal (Postmile 0-14, 2:00-9:00 PM): Although it covers this section from 2:00-5:00 PM, redness from 5:00 to 9:00 PM is more as compared to “No Rain Situation”. This demonstrates that the impact of rain on a section could be extended even after rain is over.

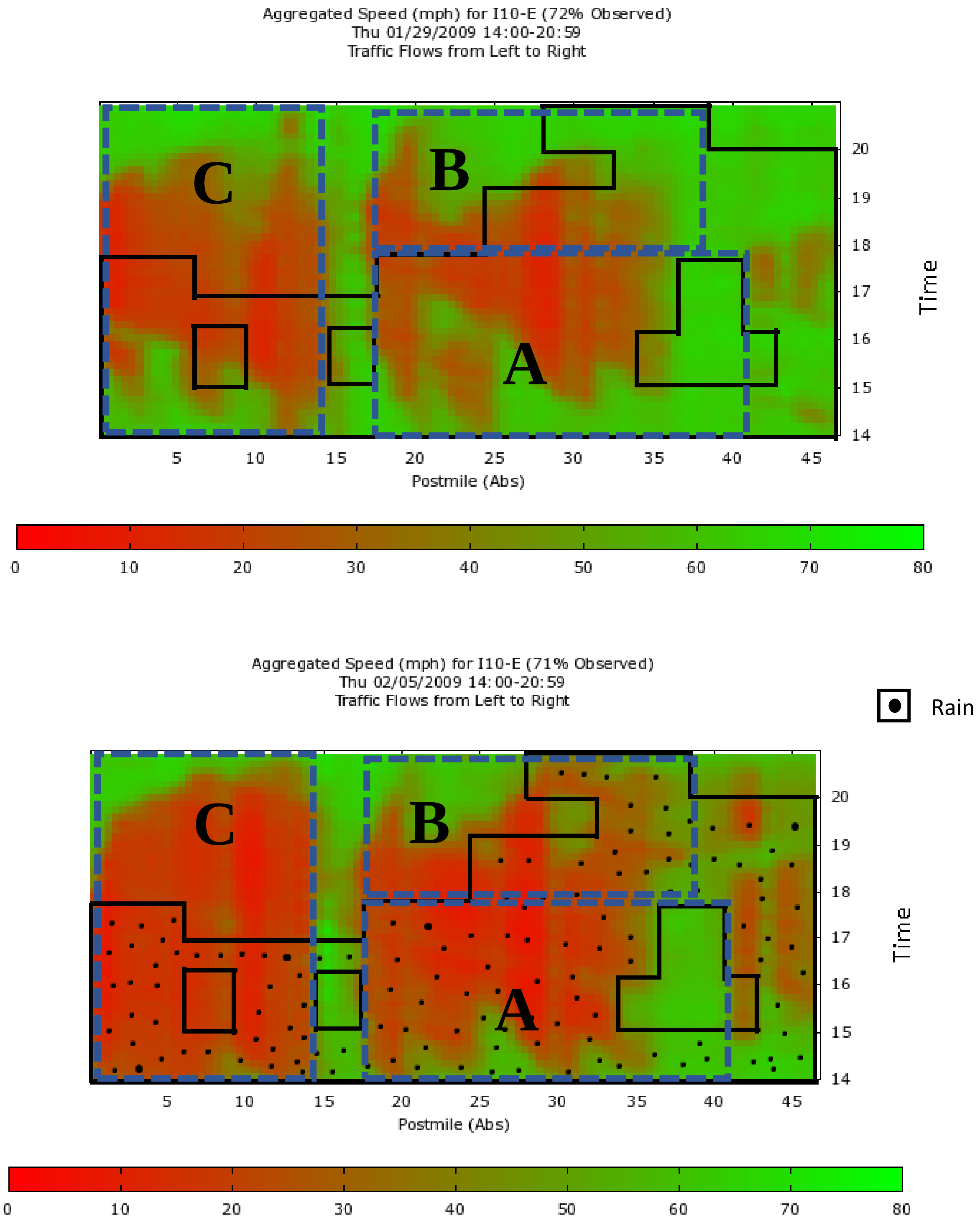

FIGURE 5 Contour plots for speed on a freeway section (29 January, and 5 February).

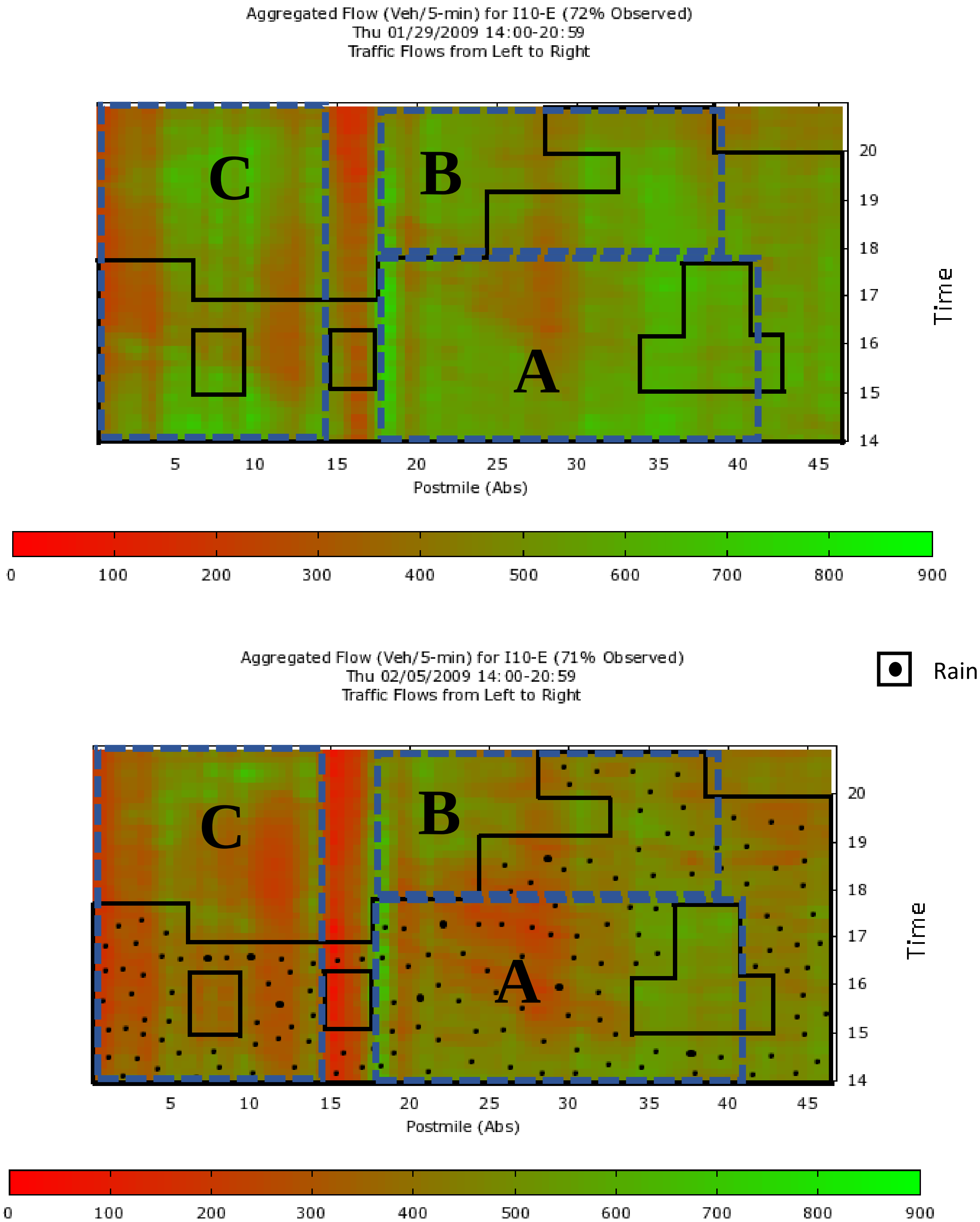

FIGURE 6 Contour plots for flow on a freeway section (29 January, and 5 February).

IMPACT ON FREEWAY CAPACITY

As one of the goals of this research is to investigate the existence of regional variations in impact of rain on traffic, this section particularly analyzes the impact of rain on freeway capacity by conducting a comprehensive comparison. The capacity and free-flow speed reductions recommended by HCM 2010, and Rakha et al. for various cities in the US are shown in Table 4 and Figure 7. It was inferred that for a dry region, the HCM has overestimated the reductions for free-flow speed, and underestimated the reductions for speed at capacity and capacity. Similarly, recommendations by Rakha et al. are underestimated for a dry region and could not be applied to dry areas such as Los Angeles. Also, regional variations may be expected for other dry regions such as Arizona, Nevada, etc. Hence, it is recommended that weather adjustment factors based on average annual rainfall should be included in the HCM in addition to previous guidelines on impact of weather.

TABLE 4 Percent Drop in Traffic Parameters for Different Cities and HCM 2010

Parameter	Rain Type	HCM 2010	Los Angeles	Baltimore	Minneapolis	Seattle
free-flow speed	Light	8.3	5.70	3.7	2	2.5
	Medium	12	6.91	5.5	3.5	6
	Heavy	16.7	8.65	8.2	6	7.5
speed at capacity	Light	3.7	11.71	9.9	4.2	8.3
	Medium	6.5	12.34	11.4	5.5	12
	Heavy	9.3	17.40	14.2	8	13
capacity	Light	2.01	10.22	10.8	11.1	10.4
	Medium	7.24	11.85	10.8	11.1	10.4
	Heavy	14.13	15.34	10.8	11.1	10.4

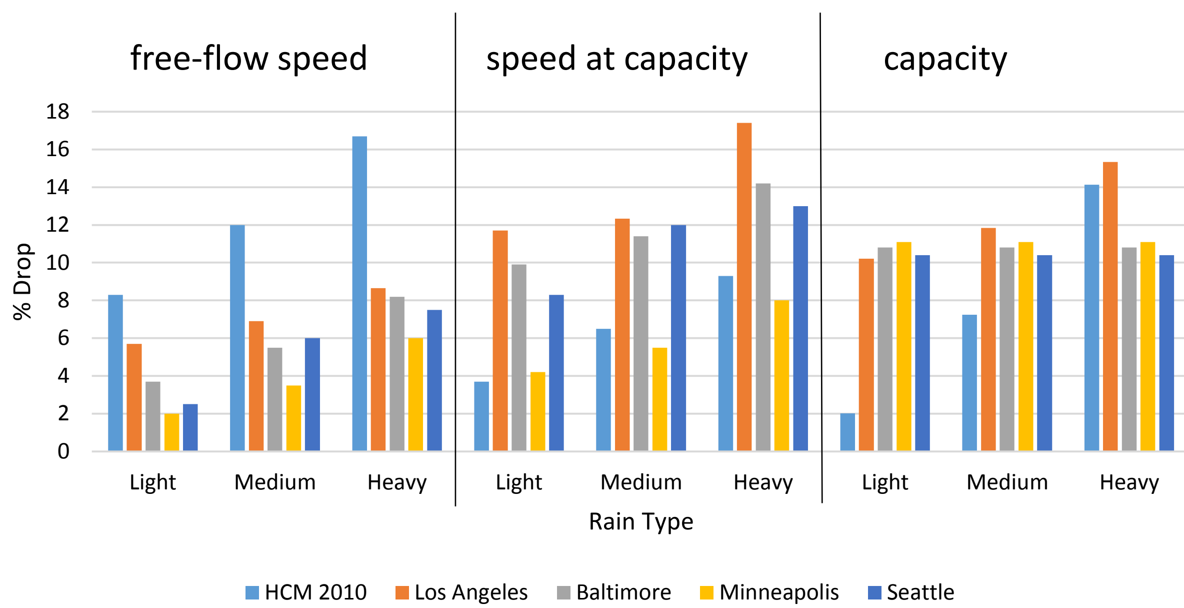

FIGURE 7 Percent drop in traffic parameters for different cities and HCM 2010.

CONCLUDING REMARKS

This study analyzed the impact of rain on traffic in a dry region and compared the data with past studies to learn if there were any regional differences. Traffic from loop detectors and rainfall from rain gauge from Los Angeles Area were analyzed to see variations in trends during various rainfall types: No rain, Light rain, Medium rain, and Heavy rain. Based on the results of analysis, some important conclusions can be drawn as follows:

1. Rain reduces the free-flow speed, speed at capacity, and capacity of Freeways and there are regional differences associated with the percentage of reduction.
2. The average reduction in free-flow speed for light, medium and heavy rain was found to be 5.7%, 6.91%, and 8.65% respectively. This reduction is less when compared to HCM 2010 and more as compared to Rakha et al.
3. The average reductions in speed at capacity for light, medium and heavy rain were found to be 11.71%, 12.34%, and 17.4% respectively which is higher than reductions in both the HCM 2010 and Rakha et al.
4. The average drop in capacity for light, medium and heavy rain was found to be 10.22%, 11.85%, and 15.34% respectively. Reductions in capacity during medium and heavy rainfall are more than reductions in both HCM 2010 and Rakha et al. whereas for light rain it is more than HCM 2010 but slightly less than Rakha et al.
5. As done in earlier studies *(9)*, Weather Adjustment Factors were computed that can be multiplied by base condition values**.**
6. There is an increase in headway with an increase in the intensity of rainfall which is consistent with past studies *(12)*.
7. speed and flow are reduced due to rainfall over a particular section of freeway and the impact can be seen in the upstream flow whereas the downstream flow is not much affected.

The reduction in various parameters cause significant changes in fundamental diagrams and these changes can be helpful to determine the changes in demand and capacity. This study, however, was not able to address changes in jam density which is a key parameter. Like many studies in the past, this study also suffered from the limitations of available processed data. For example, less rainfall in an area leads to less amount of data and a dense freeway network with large numbers of on and off ramps make it difficult to choose similar stations. Despite these limitations, an estimate of trends has been presented and an introduction to the associated limitations have suggested the need to dig deeper and address those limitations in the future.

Overall, this study revealed that there are regional variations that may vary from state to state, city to city, freeway to freeway, and even on different sections of the same freeway. Hence, a need for big data application was felt to develop a data responsive software that can access the real-time traffic (flow, occupancy,etc.) and weather data (precipitation, visibility, temp, wind, humidity) for all the traffic and nearby weather stations, and analyze it. For the purpose of accuracy, data could be collected from a much larger area such as whole Southern California, Nevada, Arizona etc for dry regions and similarly some comparitively wet regions. This may lead to an effective ramp metering in all weather conditions and ultimately traffic engineers would be able to estimate and mitigate traffic demands in advance, based on the weather forecast. This may also help the users to plan their trip and have a better estimate of travel times in advance.

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