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Extent of Highway Capacity Loss due to Rainfall

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***Abstract*—**Traffic flow in adverse weather conditions have been investigated in this study for general traffic, week day and week end traffic. The empirical evidence is strong in support of the view that rainfall affects macroscopic traffic flow parameters. Data generated from a basic highway section along J5 in Johor Bahru, Malaysia was synchronized with 161 rain events over a period of three months. This revealed a 4.90%, 6.60% and 11.32% reduction in speed for light rain, moderate rain and heavy rain conditions respectively. The corresponding capacity reductions in the three rainfall regimes are 1.08% for light rain, 6.27% for moderate rain and 29.25% for heavy rain. In the week day traffic, speed drops of 8.1% and 16.05% were observed for light and heavy conditions. The moderate rain condition speed increased by 12.6%. The capacity drops for week day traffic are 4.40% for light rain, 9.77% for moderate rain and 45.90% for heavy rain. The weekend traffic indicated speed difference between the dry condition and the three rainy conditions as 6.70% for light rain, 8.90% for moderate rain and 13.10% for heavy rain. The capacity changes computed for the weekend traffic were 0.20% in light rain, 13.90% in moderate rain and 16.70% in heavy rain. No traffic instabilities were observed throughout the observation period and the capacities reported for each rain condition were below the no-rain condition capacity. Rainfall has tremendous impact on traffic flow and this may have implications for shock wave propagation.

***Keywords*—**Highway Capacity, Dry condition, Rainfall Intensity, Rainy condition, Traffic Flow Rate.

I. INTRODUCTION

WEATHER systems profoundly influence the way human beings live and interact with the environment. They are responsible for the differences and variety of clothing, food, shelter and transportation used amongst human populations from different parts of the world. Extreme temperature, humidity and wind adversely affect human behaviour. Extreme weather events have also devastated human settlements, inundated farm lands, disrupted transportation systems, and claimed numerous human lives through the destructive forces of wind, water and extreme temperatures.

In modern times, in spite of the advances in technology, weather systems continue to cause havoc to transportation systems particularly, road, air and sea transport modes. In road transportation, adverse weather conditions significantly disturb traffic flow movements creating bottlenecks that cause delays, excessive travel times, and raise driver apprehension about safety. Increase in driverpopulations on one hand and lack of space or expensive relocations in the towns and cities on the other hand, have raised concerns about highway capacity utilizations on freeways and urban road networks.

The measurement, prediction and monitoring of highway capacity for evaluation of traffic management strategies and sustainability of efficient traffic flows in both normal and adverse weather conditions have evidently become important. Even in normal weather conditions, capacity problems arise during peak hours and at bottleneck locations such as on and off ramps, intersections, work zones, grade and curve sections, changes in road geometry, and at black spots. There is a preponderance of research work about highway capacity in normal weather available in the literature, than there is in adverse weather condition.

The aim of this paper therefore, is to examine the problem of highway capacity loss in adverse weather, particularly, rainfall and to quantify the extent to which capacity loss occurs. The rest of the paper is organised as follows: Section II deals with literature review on the subject, Empirical highway capacity estimation follows in section III. An explanation of rain effects on traffic flow is presented in section IV. The data collection procedure adopted for this study and the results are presented in sections V and VI respectively. Section VII covers capacity implications of rain and the implications for weekday and weekend traffic are presented in Section VIII. Finally, the conclusions follow in Section IX.

II. LITERATURE REVIEW

Highway capacity measurements enable traffic operators to assess current traffic flow rates on freeways and urban road networks to identify sections or points with flow constraints. The values of capacity thus obtained are used to support decisions to be made on what improvements are required at such locations. However, efforts at determining highway capacity values have not yielded consistent results. For instance, [1] obtained capacity data collected during peak periods for over 52 days in Ontario and recommended capacity values of 2,300pc/hr and 2,200pc/hr respectively for stable flow conditions and post breakdown conditions. Similarly, [2] collected capacity data at a freeway site and obtained a mean capacity value of 2,315pc/hr with a standard deviation of 66pc/hr. The Highway Capacity Manual [3], specifies the capacity of freeways to be 2,250pc/hr for free flow speeds up to 88.51km/hr and 2,400pc/hr for speeds up to 120.70km/hr. These findings among others, have raised questions on the current definition of highway capacity[3] and [4].

The breakdown phenomena took the center stage in explaining the variability of highway capacity values. Observations of the breakdown phenomena by [1], [5] and [6] in their studies, prompted the pursuit of the subject by [7-10]

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as well as by other researchers in the field. Four different maximum flows obtained from different bottleneck locations became the candidate choice among researchers for use as the value of capacity. These are: *mean queue discharge flow, maximum queue discharge flows, breakdown flows and maximum pre-breakdown*. However, [11] had established that highway capacities vary according to external factors such as dry or wet surfaces, daylight or darkness and whether it is a rural or urban freeway facility. In addition to fixed bottlenecks, the points raised by [11] add variability to highway capacity determination. It may be argued that the value of capacity will remain a variable issue unless a consistent and uniform methodology is reached among researchers.

The capacity of a highway section remains the same irrespective of the ambient conditions prevailing at a particular time and location. However, the flow rates vary depending on the strength of the disturbance which generally results from a constriction in the flow of traffic. The weather component of it, particularly rainfall behaves in a similar fashion. Studies by [12-16] have all reported drops in capacity during rainfall. In particular, [13] found decreases in travel demand by 2.9% during week days and an average of 4.1% during weekends. Similarly, [14] found significant traffic volume decreases of 1.35% and 2.11%respectively for wet and spring periods while [15] reported capacity decreases of up to 4.7% in light rain and 14% in heavy rain.

III. EMPIRICAL HIGHWAY CAPACITY ESTIMATION METHODS

Empirical highway capacity estimation can be approached through headways, volumes, volumes and speeds and through volumes, speeds and density methods. The study by [17] has given a detailed treatise on the techniques of capacity estimation using direct empirical methods as shown in Fig.1. One approach most suited to this research is the volume, speed and density method otherwise called the fundamental diagram method (FD). Using the bivariate relationships of speed-density, speed-flow and flow-density, the complete traffic state information can be furnished at current and critical states. This information is not obtainable when other empirical estimation methods are employed. Furthermore, the FD method does not require capacity measurements in the vicinity of a bottleneck. The fundamental diagrams so constructed can be used to extract information on the state of traffic. Studies by [16], [18] and [19] have used the FD to compare two traffic conditions and to compute the resulting flow rate or speed differences.

A quantitative assessment of traffic flow requires the use of flow-density and speed-density fundamental diagrams. To proceed, a linear relationship between the traffic flow variables of speed and density, first proposed by [20] is employed thus;

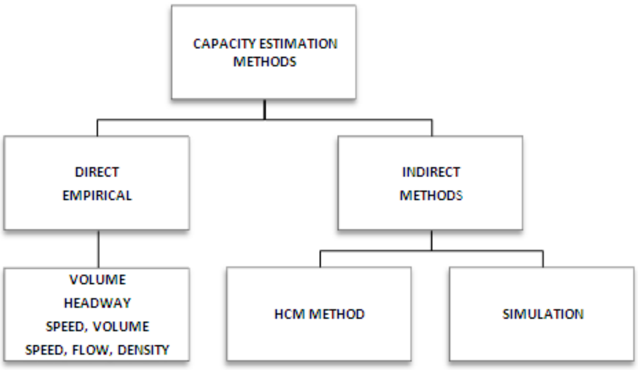

Fig. 1 Highway Capacity Estimation Methods [17]

$$u_s = u_f - \frac{u_f}{k_j} k \qquad (1)$$

From the general equation relating speed, flow and density we have:

$$q = u_s k \qquad (2)$$

To see the relationship between speed and flow, we substitute $k = q / u_s$ from (2) and this gives the speed-flow relationship:

$$u_s^2 = u_s u_f - \frac{u_f}{k_j} q \qquad (3)$$

Similarly, the flow and density relation is obtained by substituting $u = \frac{q}{k}$ and the result is:

$$q = u_f k - \frac{u_f}{k_j} k^2 \qquad (4)$$

The general form of the second degree polynomial which takes the form $q = -\beta_0 + \beta_1 k - \beta_2 k^2$ is required to model the empirical data for the flow density relationship and to predict the capacity at critical density [18].

IV. MECHANISM OF RAINFALL EFFECT ON TRAFFIC STREAM

The bivariate flow-density diagram could be used to explain the effect of rainfall on Highway Capacity. Two diagrams each representing the dry and rainy conditions are superimposed on the flow-density diagram. Initially, the traffic is in normal condition and the state of the traffic is described by the FD representing the normal condition. At the initial state of traffic, free flow speed conditions exist andthe flow could lieanywherebetween the origin and themaximum flow.

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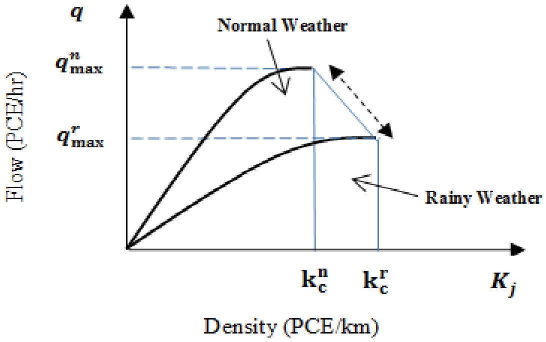

Fig. 2 Flow-Density Fundamental Diagram for Dry and Rainy Weather

Traffic flow behaviour in the vicinity of capacity (the peak flow) is influenced by inter-vehicle interactions and close packing of vehicles begin to take place. Flow rates in excess of the maximum flow leads to further rearrangement of vehicles with smaller inter-vehicle gaps. Congestion is said to have occurred. It is still possible to add more vehicles to the stream until no further addition is possible. Traffic is said to be in a jam state. This is the maximum density practically possible on a given unit length of the roadway.

When it rains, the deterioration in sight distance causes a reduction in speedand the leading vehicle in the stream slows down [21]. This causes a wave front to form and the wave front becomes the speed of the leading vehicle. On highways in the free flow regime, driver response to the rain is independent of other vehicles and no instability may result. However, the deterioration in sight distance causes a reduction in speed and a flow contraction generally occurs. On highways with high flow rates, queues build up behind the leading vehicle. This is shown in Fig. 2 as rainy weather condition. The constriction in the flow brought about by the rain is shown as the trapezoidal portion of the region between the free flow state and the rainy condition.

The slope of the line between the maximum free flow in normal condition ($q^{free}_{\max}$) and the maximum free flow in rainfall condition ($q^{r1}_{\max}$) is the flow rate change between the two conditions. Steep slopes indicate high stream flow change between dry and rain conditions, an indication of a strong perturbation. Gentle slopes are indicative of weaker perturbations and traffic can recover from this at low flow rates. At high flow rates however, traffic enters into congestion and the rainfall conditions prevail. It may be useful to explore the flow rate changes in congested states under rainfall conditions and to correlate with different rainfall intensities to determine thresholds that are consistent with any of the extended congested states.

V. DATA COLLECTION

Data for this study was collected at two sites along the Skudai-Pontian highway (J5) in Johor Bharu, Malaysia. To isolate bottleneck effect on the flow, a basic highway section 2km long was used as the data collection sites. A pneumatic tube detector was laid across the road at the sites and data was generated for three months starting from November 2011 to January 2012. Close to this site is a rain gauge station 1740m away. The traffic data was later retrieved from the detector and analysed. The data from the gauge station was used to synchronise the traffic and rainfall data to identify suitable data sets for analysis. To minimise spatial variation of the rainfall data and to obtain exact start and end times of rainfall events at the observation site, an observer was stationed at the site to record start and end times of rainfall events. Traffic data which coincided with the rainfall events were identified and classified as rainy condition. Other traffic data were classified as dry condition. The rainy condition data were further classified according to rainfall intensities and corresponding to World Meteorological Organisation standards [22].

The meteorological features at the observation sites for the period of the study are shown in Table I. It is clear from Table I that there are no extreme temperature variations at the observation sites. The maximum temperatures occur during the day while the minimum temperatures prevail during the night period. Also the wind conditions are favourable to comfortable and safe driving. The mean duration of the daylight hours throughout the period of data collection is 12hrs +03min.

TABLE I
METEOROLOGICAL FEATURES AT THE OBSERVATION SITES

Month	Sunrise	Sunset	Temp (max)	Temp (min)	Wind Speed
	MYT	MYT	°C	°C	(Km/hr)
November 2010	6.47	6.50	34	29	21
December 2010	6.53	6.55	34	25	16
January 2011	7.07	7.09	33	23	23

The composition of traffic at the study site for the duration of the observation period is shown in Table II. The average passenger car content in the traffic stream at site I was 87.31% and 88.87% at site II. The motorcycle content is 6.75% at site I and 6.62% at site II. This was filtered out of the data due to their unique mode of operation. The traffic data was then converted from vehicles/hr to PCE/hr using standard Malaysian PCE values and was analysed for daylight conditions only. The posted speed limit (PSL) on the facility is 60km/hr.

TABLE II
AVERAGE TRAFFIC COMPOSITION AT THE OBSERVATION SITES

Sites	Motorcycles	Passenger Cars	LGVs	HGVs
Site I	6.75	87.31	3.28	2.66
Site II	6.62	88.87	2.32	2.19

VI. RESULTS

The results of the study are presented by first examining the empirical fundamental diagrams for the traffic. The flow pattern is shown in Fig. 3 and Fig. 4 for the two sites. This is important because it could reveal any incidences (if any) that occurred during the observation period. The basic highway section was assumed to be incident free and this is confirmed by the flow profile for both Site I and Site II. Clearly, there are

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consistent peaks for the week day traffic and less so for the weekend traffic. The profile further reveals that the morning peak obtains at Site I while the evening peak occurs at Site II. No bottlenecks were observed and this is confirmed by the profile plots as well.

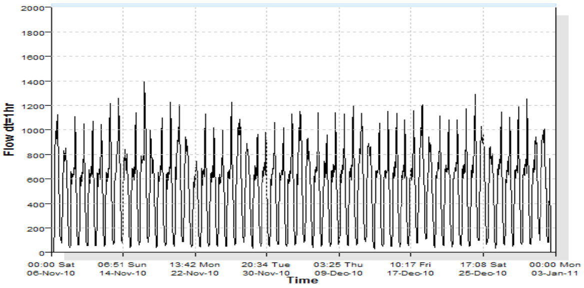

Fig. 3 Traffic Flow Profile for Site I

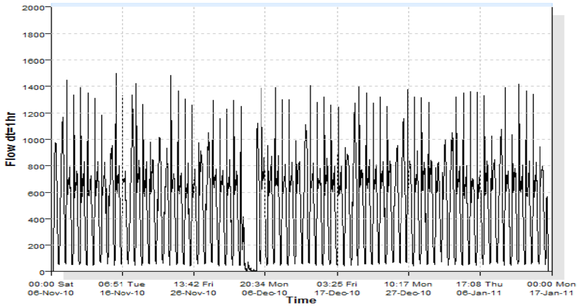

Fig. 4 Traffic Flow Profile for Site II

The empirical features of the flow are depicted in Fig. 5 to Fig. 7. Considering the shapes of the theoretical bivariate fundamental diagrams of traffic, it can be safely inferred that the facility was operating in the free flow regime of traffic in both weather conditions. The three plots need to be read in conjunction with each other to understand the operating conditions of the facilities.

A. Rainfall Effect

The effect of rainfall on the flow of traffic and speed is summarised in Tables III and IV. The mean flows for daylight hours are higher for rain condition than non-rain condition. However, the maximum flow decrease with increase in rain intensity. It may be plausible to infer that light rain condition does not disturb the flow in any way. For all parameters of the flow shown in Table III, the light rain condition surpasses the dry condition. In terms of the speed shown in Table IV, there is a decrease in mean speed between the no-rain condition and the rainy conditions. Also the mean speed decreases as the rain intensity increases. The light and moderate rain conditions maximum speeds exceeded the PSL by 15.91% and 7.13% respectively while the heavy rain condition was less than the PSL by 1.72%.

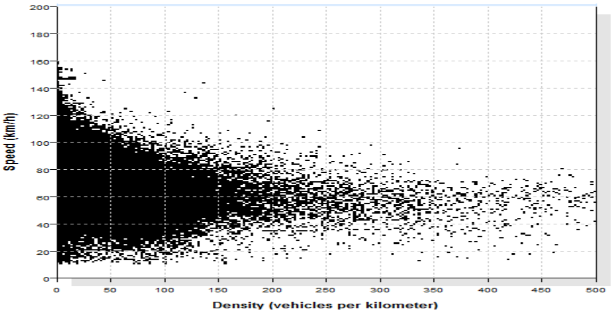

Fig. 5 Speed Density Dispersion Plot

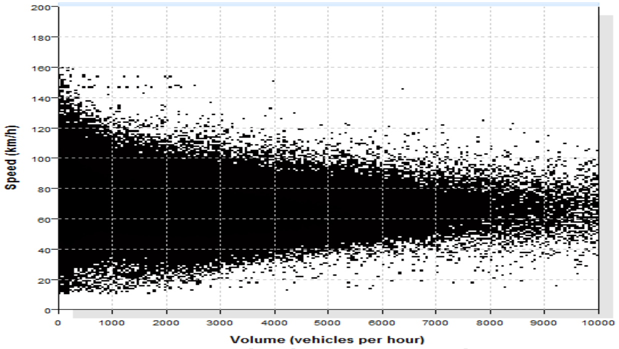

Fig. 6 Speed-Volume Dispersion Plot

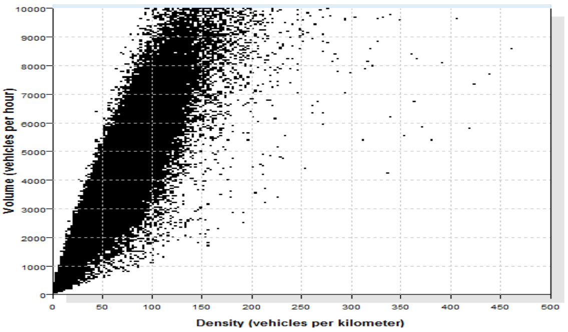

Fig. 7 Volume-Density Dispersion Plot

VII. CAPACITY IMPLICATIONS OF RAIN

The implications for highway capacity and the mechanics of the flow under rain conditions can be understood from Fig. 8 to Fig. 16. In Fig. 8, 9 and 10, the plots for dry weather and light rain conditionfor speed-density, flow-density and speed-flow are presented and are almost coincident on each other and the lines representing the light rain condition are barely visible. Thus light rain does not appreciably affect traffic flow. The free flow speed attainable under both dry and light rain conditions are respectively 64.37km/hr and 63.68km/hr. Figs. 11, 12 and 13 show the plots for dry and moderate rain condition. There is a drift in the moderate rain condition plotdownwards and this reveals the contraction in the flow and the reduction in speeds. There is also a drop in free flow speed by 4.06% between the dry and moderate rain condition.

The plots for dry and heavy rain condition are shown in Figs. 14, 15 and 16. Rain intensity in the range of 10mm-50mm cause dramatic reduction in free flow speed and flow contraction than both light and moderate rain conditions. In this study, the drop in free flow speed is 6.43%. This is lower than expected considering the timing of the study to coincide with the period of highest rainfall in Malaysia.

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TABLE III
TRAFFIC SPEED CHARACTERISTICS FOR RAIN AND DRY CONDITIONS

Speed Characteristics	Dry Condition	Rain Condition		
		Light Rain	Medium Rain	Heavy Rain
Mean (km/hr)	58.81	55.90	54.93	52.15
Median(km/hr)	58.73	55.93	55.04	52.20
Stdev(km/hr)	3.56	4.33	4.06	4.08
Max(km/hr)	76.04	69.55	64.28	58.97
Min(km/hr)	48.14	42.45	43.43	40.81
Variance	12.70	18.721	24.25	16.67
95% CI	0.20	0.31	0.56	0.70

TABLE IV
TRAFFIC FLOW CHARACTERISTICS FOR RAIN AND DRY CONDITIONS

Flow Characteristics	No Rain Condition	Rain Condition		
		Light Rain	Medium Rain	Heavy Rain
Mean(PCE/hr)	731.70	803.99	841.29	765.59
Median(PCE/hr)	690.00	792.00	792.00	736.00
Stdev(PCE/hr)	178.32	225.45	232.55	188.91
Max(PCE/hr)	1546	1632	1521	1464
Min(PCE/hr)	320	216	528	400
Variance	31799.16	50827.79	54081.58	35687.90
95% CI	9.95	15.99	32.15	32.23

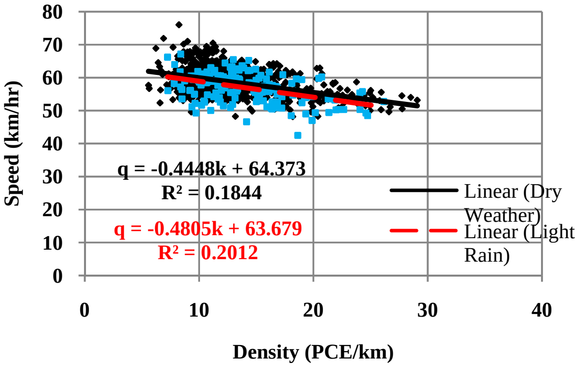

Fig. 8 Speed-Density Plot for Dry and Light Rain Condition

The flow rate reductions reflected in the capacity implications for the four conditions are summarised in Table V. The current traffic flow levels in rain condition are all higher than the dry condition. The densities in rain conditions are higher than the dry condition and the decreasing speeds in rain conditions than dry condition supports the widely held view that rainfall affects traffic flow and speeds. At the current state of traffic, the predicted states at capacity shows decreasing capacity levels with increase in rain intensity. Thus light rain, that is, rainfall of intensity less than 2.5mm will cause only 1.08% loss of capacity. Similarly, a capacity loss of6.27% will result from rainfall of moderate intensity (2.5-10mm). Heavy rainfall has a more pronounced effect and causes 29.25% loss of capacity.

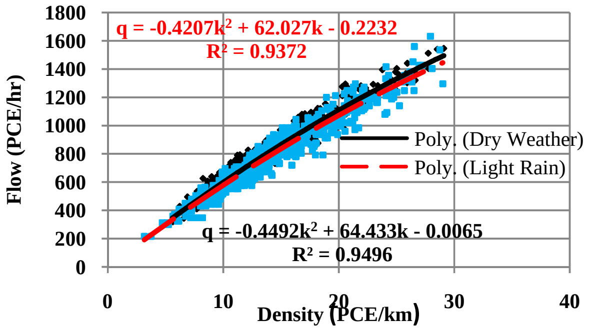

Fig. 9 Flow-Density Plot for Dry and Light Rain Condition

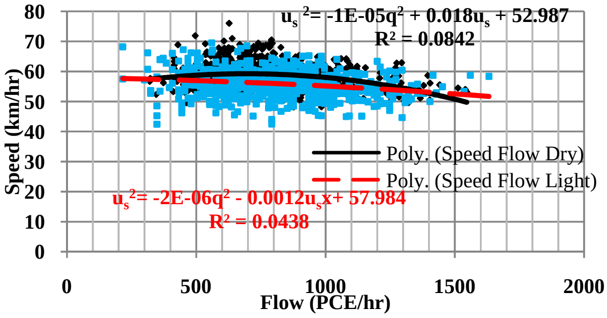

Fig. 10 Speed-Flow Plot for Dry and Light Rain Conditions

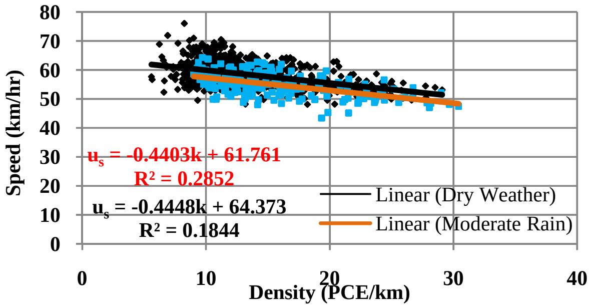

Fig. 11 Speed-Density Plot for Dry and Moderate Rain Conditions

TABLE V
CURRENT AND PREDICTED STATES OF TRAFFIC FLOW

Traffic Parameter	Dry	Rainy Condition		
		Light Rain	Medium Rain	Heavy Rain
	Current State of Traffic			
Volume	731	803	841	765
Density	12.43	14.36	15.31	14.67
Speed	58.81	55.90	54.93	52.15
	Predicted State of Traffic			
Volume	2311	2286	2166	1635
Density	71.72	73.72	70.14	54.05
Speed	32.22	31.01	30.88	30.25
Flow Rate Change		3.47	25.49	10.63

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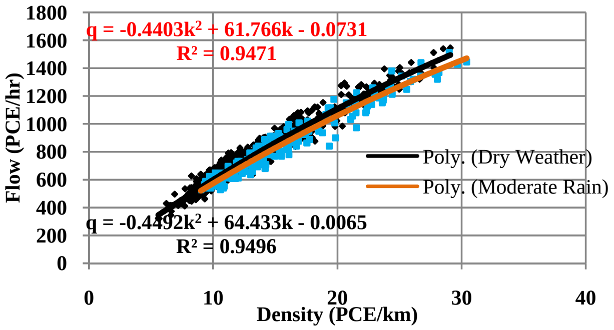

Fig. 12 Flow-Density Plot for Dry and Moderate Rain Conditions

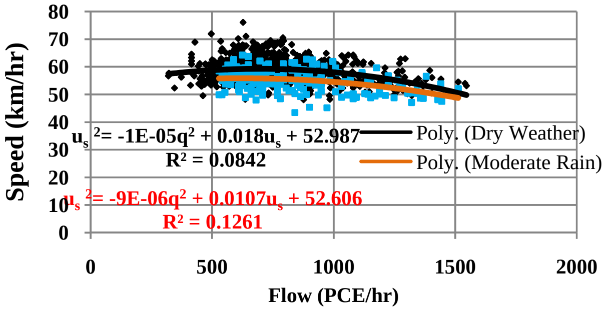

Fig. 13 Speed-Flow Plots for Dry and Medium Rain Conditions

The flow rate change between no-rain condition and any of the three rainy conditions is also shown in Table V. Physically, a flow rate change is the difference between the demand and the service rate at a bottleneck. A high flow rate change will result in queues behind the bottleneck as fewer vehicles are serviced through the bottleneck. A low flow rate change is a situation in which queues do not grow on approach to a bottleneck. In the case of rainfall, no fixed bottleneck exists. The leading vehicle slows in response to changing rain intensity. If queues grow behind a leading vehicle and no overtaking opportunities exist, or drivers opt not to overtake a high flow rate change has occurred and instabilities could follow. The resulting capacity loss will be substantial. On the other hand if the situation improves downstream of the leading vehicle, or overtaking opportunities exist or if drivers chose to overtake, queues will not grow behind the leading vehicle and the flow rate change with respect to the wave front will be low. As rainfall is a dynamic bottleneck, these processes are highly complex.

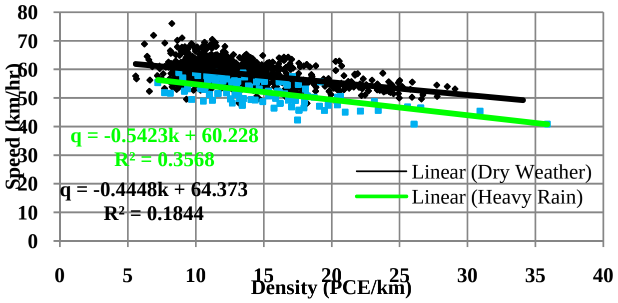

Fig. 14 Speed-Flow-Density Plots for Dry and Medium Rain

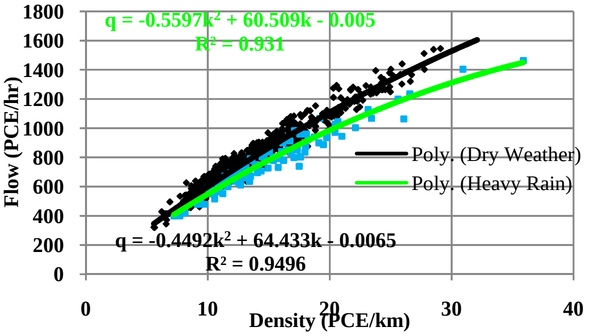

Fig. 15 Speed-Flow-Density Plots for Dry and Medium Rain

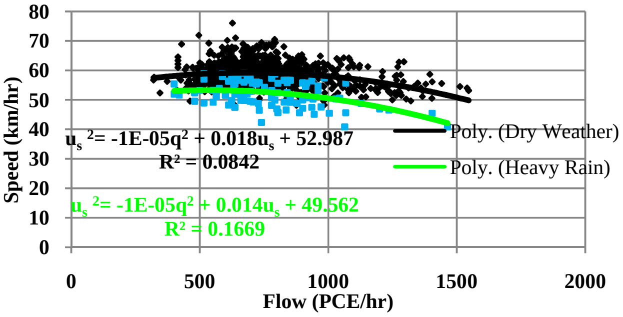

Fig. 16 Speed-Flow-Density Plots for Dry and Medium Rain

In this study, a flow rate change of 3.47km/hr was caused by light rain condition. 25.49km/hr flow rate changes were caused by moderate rain condition and 10.63km/hr flow rate change by heavy rain condition. Thus moderate rain condition is more likely to cause queue formation behind the leading vehicle to be followed by heavy rain condition. A clear indication from this result is that the capacity state in dry condition is not likely to be reached under rainfall conditions irrespective of the rain intensity. Thus there is ample capacity for additional traffic during inclement weather and it is for this reason traffic returns to normal after a rainfall event.

VIII. CAPACITY IMPLICATIONS OF RAIN ON WEEKDAY AND WEEKEND TRAFFIC

It is generally accepted that week day traffic exhibits trends dissimilar to week end traffic. Highway facilities are therefore subjected to more intense usage due to multifarious trip making within the economy during week days. Traffic disturbances during peak hour periods are more pronounced and instabilities are common. Weekend trips are mainly shopping, social and pleasure trips and are dispersed towards the country side than within the urban conurbations. The data generated from the study were separated into weekday traffic and weekend traffic and were analysed to see the effect of rain on capacity. Flow contraction and speed reduction increases with increase in rain intensity and these are observed for the weekend data too.The traffic state for both week day and weekend traffic under both non-rain and rainy conditions are summarised in Table VI.

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TABLE VI
TRAFFIC FEATURES FOR WEEK DAY

Week Day Traffic Parameter	Dry	Rainy Condition		
		Light Rain	Medium Rain	Heavy Rain
		Current State of Traffic		
Volume	708.07	891.29	793.38	691.57
Density	12.09	16.55	11.67	13.64
Speed	58.55	53.85	67.93	50.70
		Predicted State of Traffic		
Volume	2064.5	1973.7	1862.7	1116.4
Density	63.67	63.05	59.33	35.40
Speed	32.43	31.30	31.40	31.54
Flow Rate Change		+40.41	+12.28	+9.32

The trends observed for the general traffic are similarly manifested in the week day traffic. The flows for light rain and medium rain surpass that of the dry condition while the heavy rain condition was less than all other conditions. Unexpectedly, the medium rain condition speed was the highest, surpassing even the dry condition speed. At the predicted states, there is decrease in volume as the rain condition changes from light to heavy. The dry condition recorded the highest flow. The changes in capacity between the dry condition and the rainy conditions are as follows. Dry and light rain condition; 4.4%, Dry and medium rain; 9.8% and Dry and Heavy rain; 45.9%. Interestingly, there are only marginal differences in speed at capacity between the dry condition and the rainy conditions. This may mean that drivers are more consistent in behaviour with smaller inter-vehicle gaps during week days.

The characteristics of the weekend traffic shown in Table VII indicate that all the flows in the rainy conditions were higher than the dry condition with corresponding higher densities. However, the speeds decreased from dry condition to heavy rain condition. Between dry and rain conditions there was 6.7%, 8.9% and 13.1% speed reductions for light rain, medium rain and heavy rain respectively. At the critical states of traffic, the predicted volumes (Capacity) showed a decreasing trend from dry to heavy rain. The percent changes in capacity are 0.2%, 13.9% and 16.7% respectively for light, medium and heavy rain conditions.

TABLE VII
TRAFFIC FEATURES FOR WEEKEND

Weekend Traffic Parameter	Dry	Rain Condition		
		Light Rain	Medium Rain	Heavy Rain
		Current State of Traffic		
Volume	773.25	854.51	879.09	866.32
Density	12.71	15.05	15.85	16.37
Speed	60.86	56.79	55.46	52.91
		Critical State of Traffic		
Volume	1972.9	1968.0	1698.0	1642.5
Density	58.42	60.58	56.67	51.94
Speed	33.77	32.49	29.96	31.62
Flow Rate Change		+0.63	+43.63	+14.12

The speeds at critical states were however, different from that of the week day traffic; all the critical state speeds were less than the dry condition. Flow rate changes for week day and weekend traffic are similar to the aggregate traffic considered in Table V. Not all the dry condition capacity is used during rainfall.

IX. CONCLUSION

The extents of highway capacity loss under rainy conditions have been examined by this study. The study considered highway capacity changes during rainfall with general traffic data as well as with week day and weekend traffic. The macroscopic parameters of traffic flow decrease during bad weather i.e. rainfall. There is evidence of further decrease with changes in rain intensity but not necessarily in the direction of increasing rain intensity.

There was a speed drop of 4.90%, 6.60% and 11.32% between the no-rain and light rain, moderate rain and heavy rain respectively. The corresponding capacity drops for the three conditions are 1.08%, 6.27% and 29.25%.

For the week day analysis, the drops were computed as follows; 8.1% reduction in speed under light rain conditions but increase by 16.05% in moderate rain conditions. In heavy rain conditions, the speed reduced by 13.41%. Similarly, the capacity decreased by 4.40% under light rain conditions; 9.77% in moderate rain condition and 45.9% in heavy rain condition.

The week end analysis showed 6.7% reduction in speed under light rain and 8.9% under moderate rain. In heavy rain condition, the speed decreased further to 13.10%. The capacity changes for the weekend traffic showed decreases under light rain conditions by 0.20% and 13.90% and 16.70 decreases for medium and heavy rain respectively.

The overwhelming evidence from this study is that rainfall decreases speed and flow rates for general traffic and when it is segregated between week day and weekend traffic. The reduction in flow rates is a result of calmer driving during inclement weather by drivers rather than by reduction in trip making. Traffic flow during peak periods and congestions regimes that coincides with rainfall are likely to see further deterioration in driving conditions and could have implications for shock wave propagation.

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