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Quantifying Freeway Capacity Reductions by Rainfall Intensities Based on Stochastic Nature of Flow Breakdown

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Abstract**—**This study quantifies a decrement in freeway capacity during rainfall. Traffic and rainfall data were gathered from Highway Agencies and Wunderground weather service. Three inter-urban freeway sections and its nearest weather stations were selected as experimental sites. Capacity analysis found reductions of maximum and mean pre-breakdown flow rates due to rainfall. The Kruskal-Wallis test also provided some evidence to suggest that the variance in the pre-breakdown flow rate is statistically insignificant. Potential application of this study lies in the operation of real time traffic management schemes such as Variable Speed Limits (VSL), Hard Shoulder Running (HSR), and Ramp Metering System (RMS), where speed or flow limits could be set based on a number of factors, including rainfall events and their intensities.

Keywords**—**Capacity randomness, flow breakdown, freeway capacity, rainfall.

I. INTRODUCTION

RAIN reduces vehicle traction and maneuverability which affects vehicle stopping distance; heavy rain also reduces visibility distance and object recognition due to light scattering; and these impacts may prompt drivers to travel at lower speeds causing reduced freeway capacity and increased delay. However, it is not fully demonstrated how rainfall events impact freeway capacity. Although several researchers [1]-[4] have attempted to provide evidence that freeway capacity is reduced during rainfall, they assumed freeway capacity as a maximum or percentile flow rate which represents only one extreme value of flow throughout a certain period, which is thus subject to statistical sampling error. This study therefore starts from constructing an operational definition of freeway capacity by comparing the two existing concepts (fixed and stochastic) stated in [5], [6]. Follows by this, there will be a broad methodology including site selection and historical data setup. In the capacity analysis sections, histograms of flow frequencies, to check the basic shapes, and space-time plots, to quantify the capacity reductions using stochastic nature of flow breakdown, will be drawn to compare freeway capacities between different rainfall intensities.

II. LITERATURE REVIEW

Highway Capacity Manual (HCM) 2010 provides a set of fixed capacity values for different types of freeway segment (e.g. basic, weaving, and ramp) with various geometric layouts according to free-flow speeds; these capacity values are estimated by empirical speed-flow curves that are achieved during the peak period. Although HCM has been widely accepted as a professional reference for various transport engineering analysis, the speed-flow curves in HCM are only suggested for the uncongested traffic state and this manual does not cover post-congested states.

Several studies also adopted this fixed capacity concept to investigate the effect of rainfall on freeway capacity [1]-[4]. To exemplify this, [1], [2] estimated freeway capacity using the maximum observed throughput approach. Reference [3] assumed that the mean of the highest 5% of flow rates observed on a link would represent the effective capacity. Reference [4] picked up the 99th percentile flow rates as capacity values. These maximum and percentile flow rates are somewhat reasonable to indicate the capacity, in spite of that, this kind of definitions are still not very clear or inconsistent.

TABLE I
SUMMARY OF RELEVANT LITERATURES

Reference	Location	Capacity Definition	Results (Reduction %)
[1]	US	Maximum flow rate	1-3% (Trace rain) 5-10% (Light rain) 10-17% (Heavy rain)
[2]	US	Maximum flow rate	8%
[3]	US	Mean of highest 5% flow rate	4-10% (Light rain) 25-30% (Heavy rain)
[4]	Japan	99th percentile flow rate	4-7% (Light rain) 14% (Heavy rain)

Reference [5] suggested capacity as a probabilistic value which should be explained by the flow-breakdown phenomenon. Capacity was defined as the "traffic volume below which traffic still flows and above which the flow breaks down into stop-and-go or even standing traffic". The authors examined the traffic flow patterns counted at 5-minute intervals over several months at 15 different sections on German freeways, and found that the observed maximum flows closely resemble the maximum pre-breakdown flow values. Based on this finding, it was suggested that the capacity of a freeway segment can be achieved by detecting the transition from an uncongested to a congested state.

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The proposed concept of ‘capacity randomness’ which assumes that the flow rate at the breakdown point has the properties of a random variable due to variations in individual behavior and interactions.

The issue of [5], related to this study, is that the breakdown event does not necessarily occur at maximum flow and breakdown can occur at flows lower or higher than the traditionally accepted capacity values such as HCM 2010. Using this concept, this study has been carried out to detect pre-breakdown flow rates on the freeway sections to represent more reliable capacity values among rain and fine weather conditions.

III. EMPIRICAL DATA PREPARATION

UK freeway sections and its adjacent weather stations are selected for this quantitative analysis of freeway capacity by rainfall intensities. There are sufficient loop detectors and weather stations elevating the data quality; rainfall events are more frequent in this country; and regional differences such as driver behavior would be prevented by using domestic data.

A. Data Sources

Two main data sources are developed for the data analysis: 1) Motorway Incident Detection and Automatic Signaling (MIDAS) data in 2009 which are 1-minute traffic counting data (traffic stream speed, flow and occupancy) collected by the Highways Agency; and 2) Historical weather data from ‘Weather Underground’ website which provide some “open data” such as rainfall, wind-speed and temperature with 5 to 30-minute resolution.

B. Site Selection

Selected weather stations contained hourly converted precipitation data (regarded as a rainfall) with less than 15-minute data interval archived more than a year without outages. Freeway sections have at least two loop detectors within a 2-mile radius from each weather station, whilst previous studies used a radius of 2.4 miles on average [1]-[4].

Fig. 1 shows the selected sites, which are inter-urban road sections with recurrent congestion, eight loop detectors on three freeway sections and three weather stations [7].

C. Dataset Construction

To fit between 1 minute MIDAS data and 5 to 10-minute rainfall data, all the data were compiled into 10-minute intervals. It is clearly important to determine the appropriate time interval as the interval used in measuring the flow rate is influential in estimating capacity [8]. Reference [3] also stated that traffic measurements with less than 5-minute intervals cause ‘noise’. Therefore, several papers adopted or suggested 5 to 15-minute time intervals to investigate effects of rainfall [1]-[8].

Rainfall intensities were categorized as light rain (0 to 2 mm/h) and heavy rain (more than 2 mm/h), referring to proposals from the UK Meteorological Office. All the outage periods (weather stations and loop detectors) were detected and eliminated from the analysis. For example, some weather data had been skipped for several hours or days due to equipment breakdowns and MIDAS data recorded as ‘255’ also means faulty; the values such as 255 km/h or 255 veh/1min/lane data could seriously affect the overall results.

Fig. 1 Locations and flow direction of selected sites

IV. MAXIMUM FLOW RATES

Based on the previous studies in the literature review section, it could be understood that the capacity values are generally defined to be in the vicinity of maximum flow rates. Therefore, capacity reductions due to rainfall can be measured by comparing the maximum or around the maximum flow rates between fine (no rain) and rain weather conditions.

One simple analysis comparing maximum flow rates between rainfall intensities produced following results; reduction rates (Light rain: 7.3 – 15.6%, Heavy rain: 16.5 – 32.4%) are consistent between different loop detectors and the various sites. In Table II, it can be seen that there is a clear trend of decreasing maximum flow rates due to rainfall. However, it is still necessary to conduct a more comprehensive analysis of flow to support the results of this section.

Another feasible method to analyze capacity is to study the basic shape of the flow rate distribution. As the maximum flow rates only show the single extreme value which is subject to sampling error, distributions of flow rates should be checked and compared with maximum values. It is likely that the flow distributions are very similar in shape despite the occurrence of rainfall event; only difference occurs at the edges of the distributions, which represents capacity more robustly.

To check this hypothesis, histograms according to the flow rates (10 veh/h resolution) and its frequencies are drawn with the different rainfall intensities at M42 sites.

In Fig. 2, tails of the histograms are shortened by the higher precipitation rates. Basic forms of the graphs are very similar between the different rainfall intensities although smoothness of the shapes is deteriorated in rainfall conditions due to smaller sample sizes. Differences at the edge of the histograms seem to indicate a capacity reduction due to rainfall.

TABLE II
MAXIMUM FLOW RATES AT EIGHT DIFFERENT LOOP DETECTORS

	Maximum flow rates (veh/h/ln)			
	No rain	Light rain	Heavy rain	Total reduction
M42 [a]	2,298	2,024	1,836	20.1%
	2,310	2,032	1,828	20.9%
	2,300	2,032	1,820	20.9%
M25 [b]	2,024	1,876	1,690	16.5%
	2,102	1,894	1,742	17.1%
	2,164	1,950	1,796	17.0%
M1 [c]	1,900	1,650	1,284	32.4%
	1,862	1,572	1,280	31.3%
Average	2,120	1,879	1,660	21.7%

[a] Registry numbers of loop detectors: '6341A', '6342A', '6343A'
[b] Registry numbers of loop detectors: '1959B', '4963B', '4968B'
[c] Registry numbers of loop detectors: '2840A', '2879A'

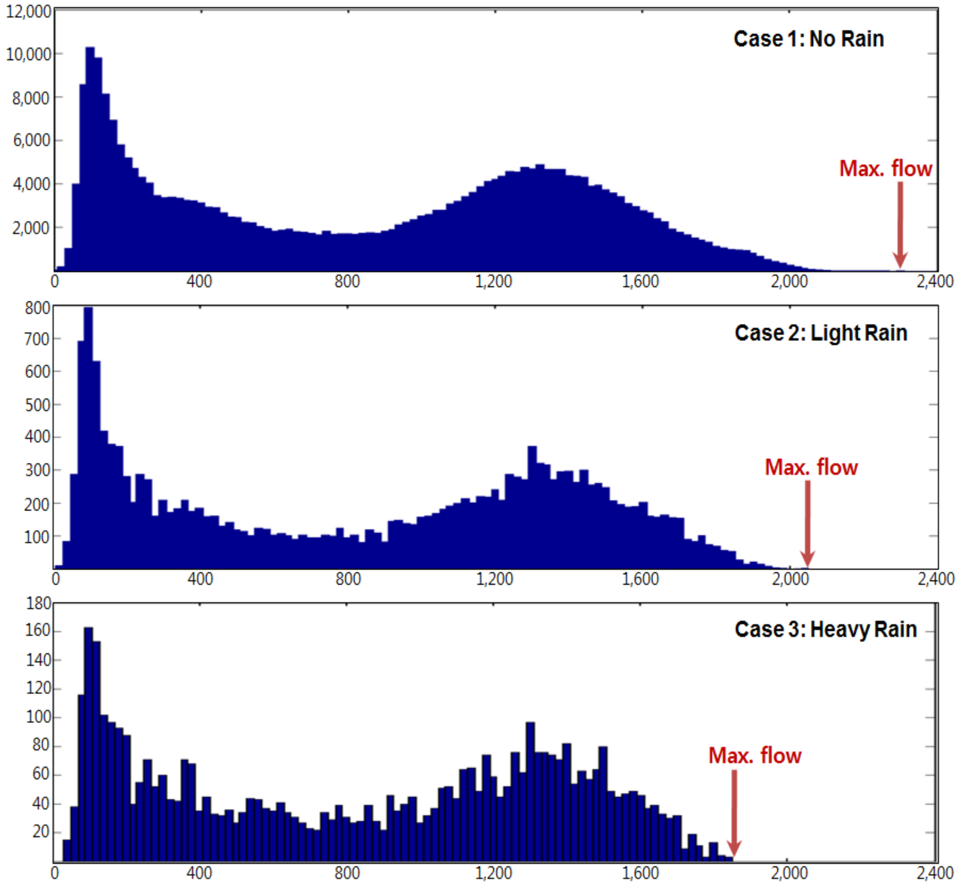

Fig. 2 Histograms of flow frequencies, 10-minute interval, M42 [X-axis: flow rate (veh/h/ln), Y-axis: frequency]

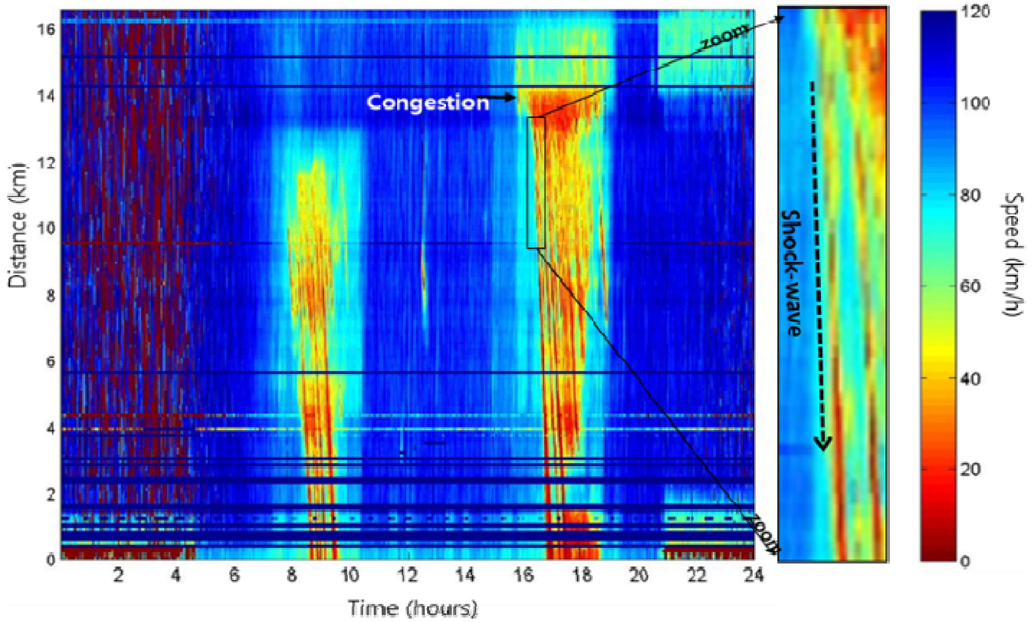

Fig. 3 Space-time plot showing congestion and shockwaves, M42

V. PRE-BREAKDOWN FLOW RATES

A. Pre-Breakdown Analysis

From the traffic operation point of view, flow breakdown occurs when the average speed of traffic drops rapidly to below a certain threshold [9]. Reference [10] suggested that congestion should be measured as the additional vehicle-hours of delay travelling below 60 mph, [11] defined breakdown as occurring when the average speed of all lanes drops below 56 mph (90 km/h) for a period of at least five minutes, and [5] set the threshold to be 45 mph (70 km/h) as a general representative for German freeways.

In this study, a capacity is defined to be the peak 10-minute throughput prior to flow-breakdown with a speed threshold of 70 km/h which is assumed by exploring collected datasets. To find the breakdown seedpoints, daily space-time plots are drawn with 10-minute MIDAS data. As the flow breakdown is typically simultaneous across all lanes of the carriageway, it is sufficient to analyze space-time plots for one lane to identify seedpoints for flow breakdown (see Fig. 4).

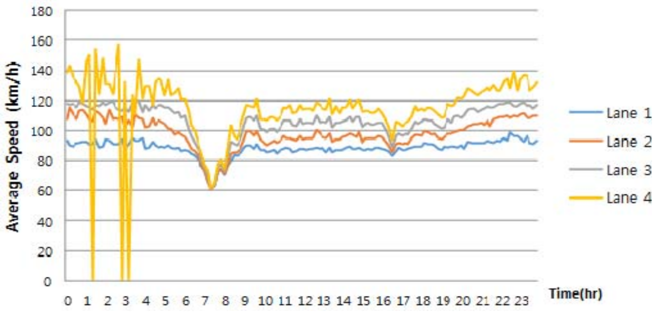

Fig. 4 Average speeds by land, 1 October 2009, M25 section

The space-time pictures are based on the second lane from the right of each carriageway (i.e. the middle lane in 3-lane situations). In Fig. 3, distance in kilometers is plotted on the vertical axis against time in hours on the horizontal axis. Color corresponds to speed in kilometers per hour, and dark blue horizontal bands indicate data outage of loop detectors. By using the visualized speed data, flow breakdown seedpoints, congestion and shock waves can be detected.

Loop detectors within ±3-km distances from the weather stations between the junctions (M25 junction 15 to 14) are used in this breakdown analysis. As the threshold speed for breakdown is defined as 70 km/h, the onset of breakdown can be identified as the left most part of the standing wave (the so-called synchronized flow) of under 70 km/h speed vehicles [12]. Fig. 5 shows the enlarged plot at M42, 3 June 2009.

In Fig. 5, each colored box represents the 10-minute average speed at a loop detector. It can be seen that the breakdown and shockwaves start from 16:50 at 6354A. Through this method of seedpoint identification, the time at the start of flow breakdown is recorded to the nearest 10 minutes.

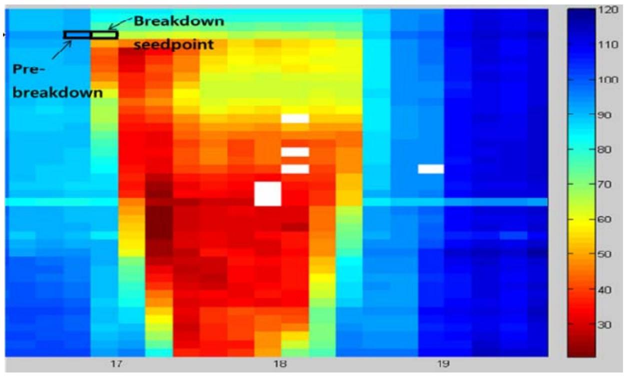

Fig. 5 Enlarged space-time plot showing breakdown seedpoint

As a result, there are 90 pre-breakdown seedpoints which include eight rainfall events observed in M25 section; Table III shows the mean pre-breakdown flow rates and its standard deviations. These numerical results indicate that rainfall has an influence on the level of pre-breakdown flow rates as the mean pre-breakdown flow value is significantly decreased by 10.1% whilst variance is increased in rain.

TABLE III
OBTAINED PRE-BREAKDOWN FLOW VALUES, M25

	N	Mean (Veh/h)	Std. Deviation
Rain	8	1684.9	186.8
No rain	80	1873.2	145.7

B. Statistical Test

To support the results above, some statistical analysis such as T-test, Analysis of Variance (ANOVA), Pearson's Correlation, and regression could estimate more reliable correlations between rain and the pre-breakdown. These kinds of parametric tests are often premised on the assumption of normal distribution; however, number of sample data for 'rain' is below the threshold of 30, where the central limit theorem for normality could be employed.

Consequently, each of the sample sets has been tested for normality, using the Kolmogorov-Smirnov test. This indicates the significance score for each sample below the 0.05 threshold, and therefore each sample set cannot be considered to comprise a normal distribution (Table IV).

TABLE IV
TEST FOR NORMALITY (KOLMOGOROV-SMIRNOV TEST)

	Statistic	Df	Sig
Rain	0.454	8	0.000
No rain	0.150	80	0.000

Significant at 5% level

One distributional-free method is the Kruskal-Wallis test which is commonly used when the measurement variables do not meet the normality assumption. The basic assumptions of this test are the data samples which come from populations having the same continuous distribution, and all data observations are mutually independent. As a result of the Kruskal-Wallis test, p-value (0.007) is acquired and this is less than 0.05 at the 95% confidence interval (Table V).

TABLE V
KRUSKAL-WALLIS ANOVA TABLE

Source	Sum of squares	df	Mean square	Chi-square	p-value
Group	4,757	1	4,756.95	7.29	0.007
Error	52,019.6	86	604.88		
Total	56,776.5	87			

Significant at 5% level

Based on the test result, there is no evidence that samples (pre-breakdown flow rates in 'rain' versus 'no rain') are drawn from the same population or equivalently, from different population with the same distribution. It is also able to suggest that sample median is significantly different from the others.

Overall, we found some evidence that distributions of pre-breakdown flow rate data can be changed by rainfall. However, more sample data are still required to quantify effects of rainfall on the onset of pre-breakdown. Therefore, further study should deal with longer period than one year.

VI. CONCLUSIONS

In this study, capacity values were measured by both constant (maximum flow rate) and randomness (pre-breakdown flow) capacity concepts. Under the constant capacity concept, maximum flow rates clearly decreased (roughly 10-30%) by rainfall. However, more accurate capacity values should be obtained by detecting pre-breakdown flow rates.

The pre-breakdown approach figured out 10.1% mean capacity reduction at the M25 section. Conducting Kruskal-Wallis test found some statistical evidence to support that the sample distribution and median capacity value are changed by rainfall. More detailed correlations between the variables (capacity and rainfall) may need to be quantified with larger data samples. Therefore, further studies should deal with more sites and longer periods to collect sufficient data.

Potential application of this study lies in the operation of traffic management schemes such controlled freeways, where speed limits could be set based on a number of factors, including rainfall events and their intensities.

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