Available online at www.sciencedirect.com

ScienceDirect

Procedia - Social and Behavioral Sciences 96 (2013) 270 – 279

Procedia
Social and Behavioral Sciences

13th COTA International Conference of Transportation Professionals (CICTP 2013)

Saturation Flow Rate and Start-up Lost Time of Dual-left Lanes at Signalized Intersection in Rainy Weather Condition

Hongyun SUN[a], Jinshun YANG[a, *], Ling WANG[a], Linbo LI[a], Bing WU[a]

[a]*Key Laboratory of Road and Traffic Engineering of Ministry of Education, Tongji University,*

No.4800 CaoAn Road, Shanghai 201804 ,China

Abstract

This study aims at finding out the difference of saturation flow rate and start-up lost time at dual left lanes between normal and rainy weather. It is based on the investigation of a signalized intersection in Shanghai. The result shows that compared to clear weather, saturation flow in rainy weather decreases by 3-7 percent and each lane's start-up lost time rises by 21-31 percent. However, comparing light-medium rainy weather to clear weather, the statistical difference of each of these two parameters is not significant.

Keywords: dual left lanes; saturation flow rate; start up lost time; rainfall; wet pavement

1. Introduction

In recent years, the occurrence of various adverse weather events or meteorological disasters is increasing around world. There is no doubt that these abnormal weather conditions have an significant influence on roadway environment, which is likely to cause more severe traffic accidents and traffic congestion. Hence traffic operation at signalized intersection under adverse weather draws more attentions among researchers. Majority of published study reports and papers concentrated on snow and ice weather in winter, and only a few number of studies focused on impacts brought with rainfalls. It is well known that the impacts of roadway physical factors and traffic factors, for example, heavy vehicles, lane width, grade and turning radius on traffic flow parameters were

* Corresponding author. Tel.: (86)15921564807; fax: 021-69588152.
E-mail address: jinshun2006@126.com

doi:10.1016/j.sbspro.2013.08.034

well studied and the conclusive results were drawn. However, the researches which intended to study the influence of rainy weather condition on traffic flow are very limited.

This study aims at assessing the impact of rainfall on traffic saturation headway and start-up lost time of dual-left lanes in urban signalized intersection, and then determining whether the differences of headway and start-up lost time between various lane locations or weather conditions are statistically significant.

2. Literature review

Saturation headway and start-up lost time are two key parameters in intersection design and control. They are also hard to precisely determine in reality because of many influence factors. As environment condition as concerned, previous studies at home and abroad provided several observation results about saturation flow rate and start-up lost time under rainy weather or wet pavement condition, only caused by rainfall events. However, most of those results are based on the through lane traffic operation data of intersections. Chi-Hyun and Keechoo (1998) concluded that rain resulted in 4-13% decline of intersection saturation flow rate compared to dry weather flow rate. Martin & Perrin (2000) maintained that the average saturation flow rate under rainy weather would reduce by 6%, and different precipitation levels would cause different decline rate. The rain, usually along with wet pavement condition, seemed to have little impact on start-up lost time, as the 35 samples indicated that the average lost time changed from 2.0 seconds to 2.1 seconds in their study. That means, the average start-up lost time increased by 5% in rainy weather and wet pavement condition. Adel and Seli (2004) collected and processed traffic flow data in Burlington, Vermont during 2002~2003 and 2003~2004 winter season, and found that the saturation flow reduction rate was 2-3%. They also gave the weather condition pairs not showing statistical differences for saturation headways, one of which is dry pavement condition versus wet pavement condition. Liu and Cui (2007) analyzed how the rainfall decreased intersection capacity by means of reducing friction coefficient and low visibility, and the average intersection capacity of one 159-seconds-long cycle changed from 229 vehicles of the clear weather to 203 vehicles of the rain weather.. Virginia and Andrew (2011) also suggested that saturation flow reduction rate during rain events ranged from 0-4% for light rain and 3-9% for moderate rain intensities. Janusz, Krzysztof, and Marian (2011)possessed that the relative decline in average saturation flow in relation to rain-free weather conditions was 8.5-12.3% in long duration rainfalls, about 3.6% in short duration rainfalls. Johannes and Henk (2011) considered the impact of both weather and lane configuration, and gave three reduction percent of saturation flow under light precipitation or wet road conditions, which were respectively 8.3%, 5.5% and 3% while the number of through lane were 1,2 and 3.

To sum up, saturation flow rate and start-up lost time are very likely to be influenced by rain events or wet pavement, regardless of time and location. But owing to the complex relationship among driver, vehicle, road and environment, there is no agreement on the range of variation of these two parameters. Therefore it is worthy to study the extent what the rainfall events have impact on right or left lane traffic operation, and the purpose of this paper lies in this point.

3. Methodology and Data

3.1 Methodology used in this paper

The whole objective can be divided into the following three components:

- Classify and clean original survey data according to rain intensity and pavement condition.
- Calculate saturation flow rate and start-up lost time respectively in terms of mean saturation flow and mean start-up lost time.
- Carry on hypotheses testing of equal mean between subsample pairs under different weather conditions or lane locations.

So the complete technical methodology is shown in Figure 1.

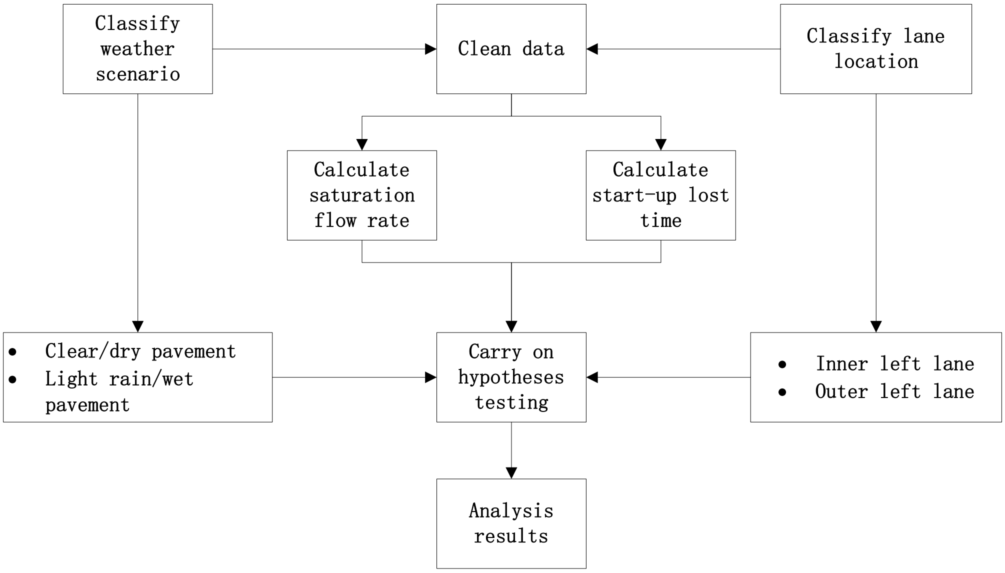

Figure 1 Research Methodology

The individual headways was the difference between time recorded when the front axles of two sequential vehicles passed the stopline, and the saturation headway is obtained by averaging headways from the 6th headway to 15th headway. Many studies suggested that the saturation condition was stable from the 6th vehicle and the first four headways of one queue should be disregarded owing to the fluctuations found in actual pre-processing of survey data. Summarizing previous relevant studies (Li & Prevedouros,2002 and Yang, Zhuang &Li,2006) , this study calculates saturation flow rate as follow:

$$h_i = T_i - T_{i-1} \qquad i=2,3... \tag{1}$$

$$h_1 = \text{SRT} + \frac{T_5 - T_1}{4} \tag{2}$$

$$h_s = \frac{\sum_{i=6}^{15} h_i}{10} \tag{3}$$

Where

i=queue position, i = 2,3…;

h_i =headway of vehicle(i);

h_s =saturation headway;

SRT = starting response time of first vehicle, generally assuming 0.8-1.2s;

T_i = time recorded when the front axle of vehicle (i) passed the stopline.

The saturation flow rate(S) is

$$S=\frac{3600}{h_s} \tag{4}$$

Startup lost time (SULT) is the sum of the SRT of the first vehicle in the queue and the additional time it took the first five vehicles to discharge. Thus,

$$SULT=SRT+\sum_{i=2}^{5}h_i-4*h_s \tag{5}$$

3.2 Road condition and traffic volume

The surveyed four-leg signalized intersection, which is named Xujiahui road & Luban road intersection. It is located at Luwan District of Shanghai city. Two field observations VCR1 and VCR2 were both made by video camera on 04/SEP/2012 and on 09/OCT/2012. VCR1 began at 3 p.m. and ended at 5 p.m. . VCR2 began at 3 p.m., and ended at half past 5 p.m. . Besides, the westbound approach traffic operation was shoot and used in this study because it has a dual-left lanes, three right lanes and two through lanes. For convenience's sake, the outer lane near the road side and inner lane near road centre line of this dual-left lane are labeled as L1 and L2 respectively thereinafter.

On one hand, the width and grade of two left lanes are equal, being 3.5m and 0% respectively. Figure 2 shows the video screenshots under different weather conditions. On the other hand, traffic volume per hour and the percent of heavy vehicles of two left lanes are very consistent, being 350 vehicles and 3% respectively. The detailed statistic is shown in Table 1.

Figure 2 video screenshots of field observation(a)04/SEP/2012; (b)09/OCT/2012

Table 1 traffic volume and percent of heavy vehicles of each of dual-left lanes

	Volume per hour		Percent of heavy vehicles	
	L1	L2	L1	L2
Clear day	331	331	3%	2%
Rain day	359	382	3%	3%

3.3 Weather scenarios classification

The weather data is obtained from the open online source, mainly from the website of The Public Weather Service Center of China Meteorological Administration (CMA). It released several common meteorological elements' hourly statistics, such as temperature, relative humidity, precipitation, wind direction and wind power. The nearest meteorological observatory from survey site is Xujiahui Meteorological Observatory, whose straight-line distance from survey site is 4km. The hourly rain intensity, from 8 p.m.,03/SEP/2012 to 8 p.m.,04/SEP/2012, is shown in Figure 3.

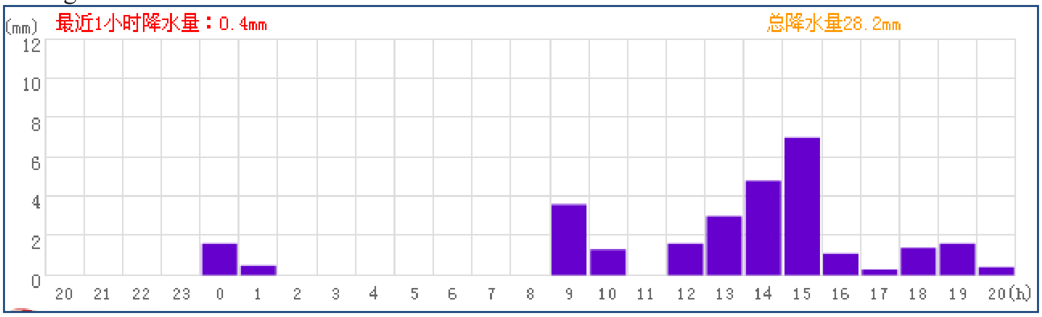

Figure 3 hourly rain intensity at Xujiahui Meteorological Observatory

From above graph and field pavement image, the rainfall level on 03/SEP/2012 belonged to the light rain category in the light of China's meteorological grade division standard. Hence two weather conditions are classified and they are clear day/dry pavement and light rain/wet pavement. For convenience's sake, the former weather condition and the latter weather condition are labeled as W1 and W2 respectively thereinafter. Hereinafter the rainy day in this study limits to the weather with light rain.

3.4 Data reduction and sample size

These first-hand data should be screened and reduced before they will be used in the following data processing phase. Herein there are three principles to ensure the high-quality data. Firstly, the headway should belong to small vehicle-small vehicle category. Secondly, only those cycles which have no less than 20 vehicles in queue at the green beginning of that cycle are adopted because of traffic saturation condition requirement. Lastly, headways from the 1th vehicle of queue to the 15th vehicle of queue are selected, among which the saturation flow rate calculation begins from the 6th vehicle and the start-up lost time calculation begins from the 1st to 5th vehicle as mentioned in Section 3.1. In the end, a dataset was obtained, which is shown in table 2. It consists of 994 headways, including the first 4 headways of each of 71 cycles.

Table 2 number of headway by lane and by weather

lane	weather	Number of headway	Total by lane
L1	W1	196	476
	W2	280	
L2	W1	154	518
	W2	364	
Total by weather	W1	350	994
	W2	644	

4. Results Analysis

4.1 Saturation headway and saturation flow rate

The original data were firstly preprocessed, mainly including individual headway calculation and data reduction illustrated in the preceding part. Then we use SPSS statistics software to obtain mean saturation headway of each lane and of both weather condition according to the formula (3). The result is showed in Figure4.

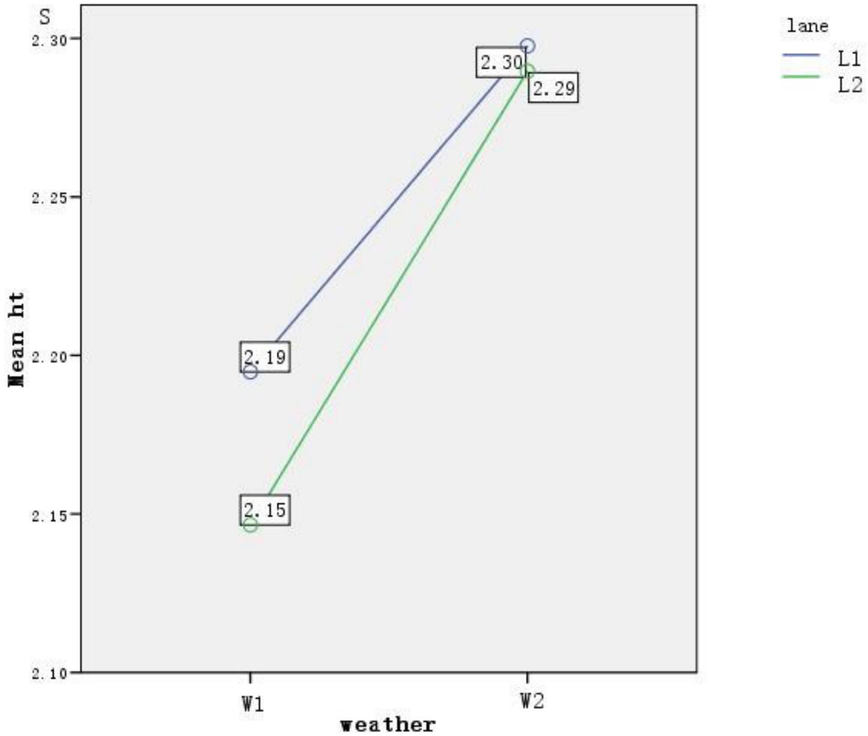

Figure 4 saturation headway variations by lane and by weather

From the figure above, the study find that saturation headway of each lane increases as weather condition changes from W1 to W2. In detail, the increase rate of L1 saturation headway is 5% from 2.19s to 2.30s. Meanwhile, the increase rate of L2 saturation headway is 8% which is from 2.15s to 2.29s. The increase range of saturation headway of each left lane from clear day to rainy day are 0.11s and 0.14s respectively, and saturation headway of inner lane had a bigger increase rate than that of outer lane.

The statistics of calculated saturation flow is showed in table 4 and figure 5. As is seen from the table, saturation flow of each lane declined as weather condition became worse from W1 to W2. In detail, the decrease percent of L1 lane saturation flow is 3% from 1741 pcu/h to 1687 pcu/h while the decrease percent of L2 lane saturation headway is 7% from 1800 puc/h to 1664 pcu/h. The inner lane traffic operation deteriorated more than the outer lane traffic operation and the standard deviation of saturation flow of each lane became smaller under rainy weather. The decrease percent of saturation flow under rainy day is consistent with the studies of Chi-Hyun and Keechoo (1998), Martin and Perrin (2000) and Virginia and Andrew (2011).

Table 4 saturation flow statistics by lane and by weather

lane	weather	N	Mean	Std. Deviation	Kurtosis	Skewness
L1	W1	140	1741	464.430	-.159	.121
	W2	200	1687	423.297	.131	-.087
	Total	340	1780	440.837	.019	.030
L2	W1	109	1800	562.287	-.079	.435
	W2	260	1664	412.693	.432	.329
	Total	369	1704	465.312	.549	.508
Total	W1	249	1767	509.333	.029	.336
	W2	460	1674	417.041	.257	.143
	Total	709	1707	453.429	.316	.296

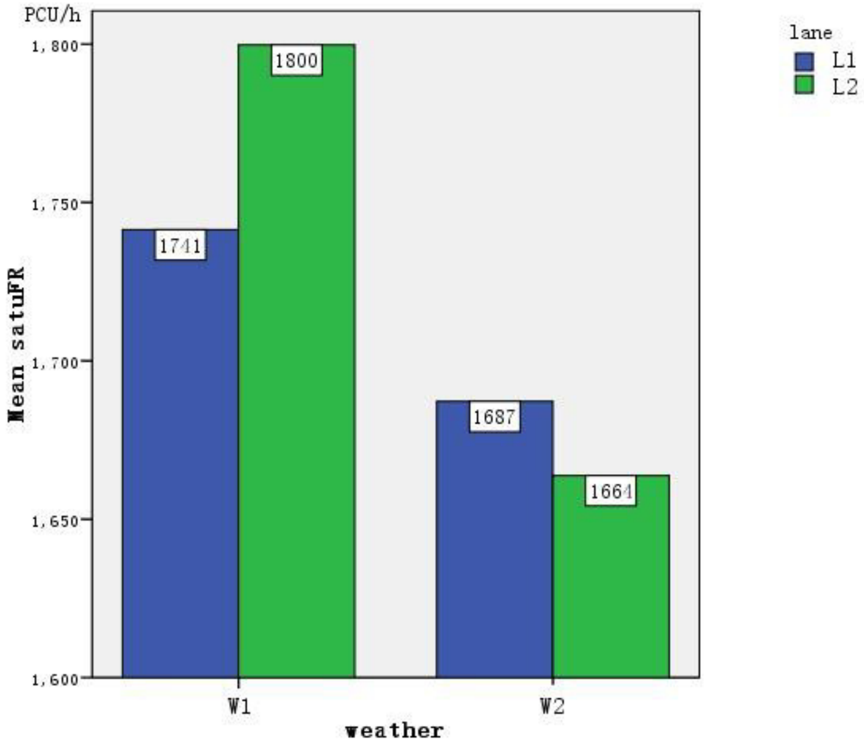

Figure 5 saturation flow rate variations under different weather conditions

Now that both lane location and weather condition have impact on saturation flow rate in the average sense, then the more concerned question is that whether those impacts are statistically significant or not? We further divide the sample into several subsamples, which are listed in table 5.

Table 5 four subsamples of saturation flow

Subsample	Data source description
SF_L1W1	only including saturation flow of L1 lane under W1 weather condition
SF_L1W2	only including saturation flow of L1 lane under W2 weather condition
SF_L2W1	only including saturation flow of L2 lane under W1 weather condition
SF_L2W2	only including saturation flow of L2 lane under W2 weather condition

The distribution of these 4 subsamples was firstly tested with normal distribution, and all subsamples pass the test except SF_L2W2. Then one-way ANOVA tests of the other three subsamples were taken to determine if influence of different lane location or different weather on traffic parameters show statistically significant at the 95% confidence level. And the results were summarized in table 6. The study finds that weather condition doesn't show statistical difference for saturation flow. The insignificant difference between saturation flow of W1 and of W2 is consistent with study of Adel and Seli (2004). Besides, impact of lane location neither showed statistical difference for saturation flow rate.

Table 6 weather condition and lane location pairs test of statistical difference for saturation flow

Condition pairs	P value of ANOVA test	Saturation flow is significant at the 0.05 level
SF_L1W1 versus SF_L1W2	0.07	NO
SF_L1W1 versus SF_L2W1	0.46	NO

4.2 start-up lost time comparisons

Similar to the processing of saturation flow, the mean start-up lost time is calculated by formula (5) and other statistics are shown in table 7 and figure 6. Obviously cycle start-up lost time of each lane increases as weather condition becomes worse from W1 to W2. In detail, the increase percent of L1 lane start-up lost time is 21% from 2.80s to 3.40s while the increase percent of L2 lane start-up lost time is 31% from 2.21s to 2.90s. Start-up lost time of inner lane had a bigger increase than that of outer lane.

Table 7 start-up lost time statistics by lane and by weather

lane	weather	N	Mean	Std. Deviation	Kurtosis	Skewness
L1	W1	14	2.80	1.522	.078	.909
	W2	20	3.40	2.281	.422	.730
	Total	34	3.15	1.999	.824	.905
L2	W1	11	2.21	3.130	-1.647	-.248
	W2	26	2.90	2.880	2.009	-.554
	Total	37	2.70	2.930	.603	-.448
Total	W1	25	2.54	2.330	-.347	-.360
	W2	46	3.12	2.620	1.813	-.268
	Total	71	2.92	2.520	1.181	-.245

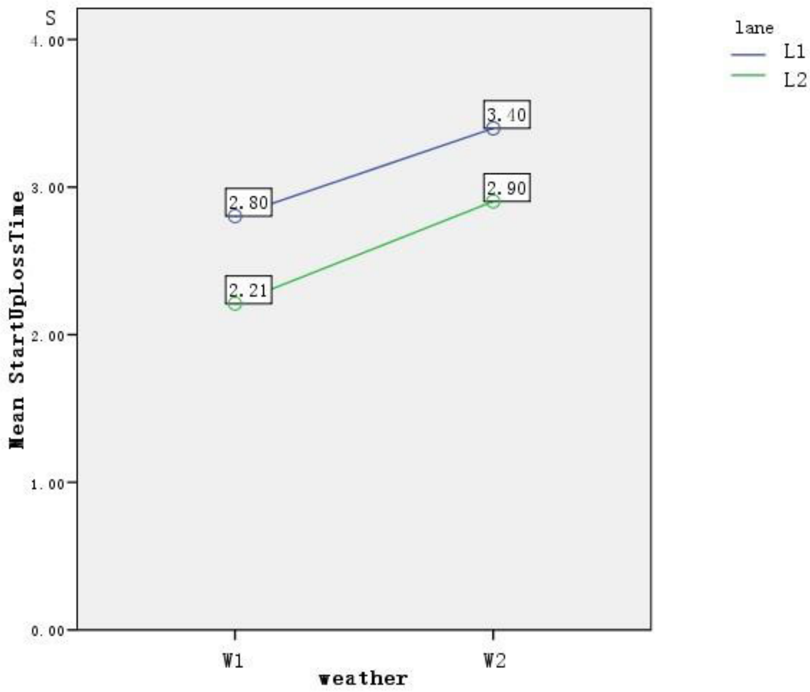

Figure 6 start-up lost time variations under different weather conditions

Now that both lane location and weather condition have impact on start-up lost time, then the more concerned question is that weather those influences are statistically significant or not? We further separated the sample into several subsamples, which are listed in table 8.

Table 8 four subsamples of start-up lost time

Subsample	Data source description
ST_L1W1	only including start-up lost time of L1 lane under W1 weather condition
ST_L1W2	only including start-up lost time of L1 lane under W2weather condition
ST_L2W1	only including start-up lost time of L2 lane under W1 weather condition
ST_L2W2	only including start-up lost time of L2 lane under W2 weather condition

Each sample distribution of these 4 subsamples was firstly tested with normal distribution, and all subsamples pass the test except ST_L1W1. Then one-way ANOVA tests of the other three subsamples were used to determine if influence of different lane location or different weather on start-up lost time show statistically significant at the 95% confidence level. And the results are summarized in table 9. The study finds that weather condition doesn't show statistical difference for start-up lost time. Besides, impact of lane location neither showed statistical difference for start-up lost time.

Table 9 weather condition and lane location pairs test of statistical difference for start-up lost time

Condition pairs	P value of ANOVA test	Start-up lost time is significant at the 0.05 level
ST_L1W2 versus ST_L2W2	0.53	NO
ST_L2W1 versus ST_L2W2	0.52	NO

5. Conclusions

The saturation flow rate and start-up lost time of dual-left lanes at signalized intersection both in clear weather and in rainy weather were separately calculated and compared using video data in this paper, and statistical differences for these two parameters under different weather conditions or lane locations were analyzed by ANOVA statistical method of SPSS software. In the end, two main conclusions are drawn from this study:

- The saturation flow and start up lost time of both left lanes decrease by 3-7% and 21-33% respectively in rainy weather. The impact of weather condition on the inner left lane exceeds that of outer left lane on the whole.
- Though the change ranges of saturation flow rate and start-up lost time of each lane of dual-left lanes under different weather condition were different on average, there are no statistical differences between these two parameters which light-medium rain weather condition or lane location results in.

In the future research, the sample should cover more signalized intersection under various grade precipitations, especially on heavy rain with long duration. The regression method may be used to distinguish influence factors on saturation flow rate and start-up lost time under adverse weather.

Acknowledgements

The research is funded by National 863 Plan Thematic Project-"Key Technology of Area Traffic Collaborative Control of Big City "(No. 2011AA110305).

References

Shin, C. and K. Choi (1998). Saturation flow rate estimation under rainy weather conditions for on-line traffic control purpose. *KSCE Journal of Civil Engineering*, 2 (3): 211-222.

Martin, P. T. and J. Perrin, et al. (2000). Inclement weather signal timings, University of Utah, Mountain-Plains Consortium.

Sadek, A. W. and S. J. Amison-Agbolosu (2004). Validating Traffic Simulation Models to Inclement Weather Travel Conditions with Applications to Arterial Coordinated Signal Systems. Report NETCR 47. Storrs, Connecticut

Liu Weidong and Cui Shuhua (2007).Studies on Capacity of the Signalized Urban Road Intersections Influenced by Rainfall Climatic Conditions. *JOURNAL OF LIAONING PROVINCIAL COLLEGE OF COMMUNICATIONS* (4): 3-5.

Sullivan, A. and V. P. Sisiopiku, et al. (2011). Impacts of Signal System Timings on Rain Related Congestion. *International Journal of Engineering and Industries* (2):1-12

Chodur, J. and K. Ostrowski, et al. (2011). Impact of Saturation Flow Changes on Performance of Traffic Lanes at Signalised Intersections. 6TH INTERNATIONAL SYMPOSIUM ON HIGHWAY CAPACITY AND QUALITY OF SERVICE. Stockholm, Sweden June 28 – July 1, 2011

Asamer, J. and H. J. Van Zuylen (2011). Saturation Flow Under Adverse Weather Conditions. *TRANSPORTATION RESEARCH RECORD*(2258): 103-109.

Li, H. L. and P. D. Prevedouros (2002). Detailed observations of saturation headways and start-up lost times. TRAFFIC FLOW THEORY AND HIGHWAY CAPACITY 2002: HIGHWAY OPERATIONS, CAPACITY, AND TRAFFIC CONTROL(1802): 44-53.

YANG Xiaoguang, ZHUANG Bin and LI Keping(2006). Analysis of Saturation Flow Rate and Delay at Signalized Intersection. *JOURNAL OF TONGJI UNIVERSITY(NATURAL SCIENCE)* (6): 738-743.

The Public Weather Service Center of China Meteorological Administration (CMA). *Weather Live on the hour*[EB/OL].2012.09.04 http://www.weather.com.cn/weather/101020100.shtml