Impact of Rainfall Condition on Traffic Operation of Urban Road Network

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Abstract: In this work, we investigate the impact of rainfall intensity on the traffic volume of different links in the Bangkok road network using traffic data obtained from Bluetooth detectors placed at intersections. For our analysis, we utilize the Macroscopic Fundamental Diagram (MFD) to compare the traffic flow rates across the various road links in the city in a variety of conditions, namely, no rainfall, light rain, moderate rain, and heavy rain (raining all days). To categorize the rainfall intensity for a particular day, the Thiessen method is used to collate the rainfall data across the meteorological stations located in Bangkok. The results of the empirical analysis over an observation period of 105 days show that rainfall intensity has a strong correlation with MFD parameters, namely, the weighted flow, weighted speed, and weighted density value. Particularly, all day rainfall causes an average daily reduction of 5.01%, 4.15% and, 3.16% for weighted traffic flow, weighted traffic speed, and weighted traffic density, respectively, across all road links in the central business district in Bangkok. This shows that rainfall intensity has a significant impact on the traffic characteristics of an urban road network.

Keywords: Rainfall, MFD, Thiessen, Bluetooth, T-test

1. INTRODUCTION

Climate change has caused frequent adverse and extreme weather events that negatively influence the performance of transport systems. An investigation into the effect of weather variables on transport systems concluded that rainfall had the most impact among all the weather variables. A negative correlation between traffic volume and amount of rainfall has been investigated (Billot, El Faouzi, & De Vuyst, 2009; Manual, 2000; Rakha, Farzaneh, Arafeh, & Sterzin, 2008; Unrau & Andrey, 2006). Understanding the effect of the rainfall on transportation performance has the potential to provide guidance for transportation management and urban planning in cities that are frequently affected by floods. Traffic flow theory is required to rationally explain the change of traffic phenomena under different weather conditions that are observed in road networks.

The Macroscopic Fundamental Diagram (MFD) is used to understand traffic flow characteristics in complex urban networks (Daganzo & Geroliminis, 2008; Geroliminis & Daganzo, 2007, 2008). The MFD was developed to establish a relationship between volume and density from empirical data. It is also used to evaluate the performance of traffic control strategies in a network. The MFDs of flow and density, density and speed, and speed and flow are important to thoroughly understand the effects of rainfall on characteristics of traffic on highways.

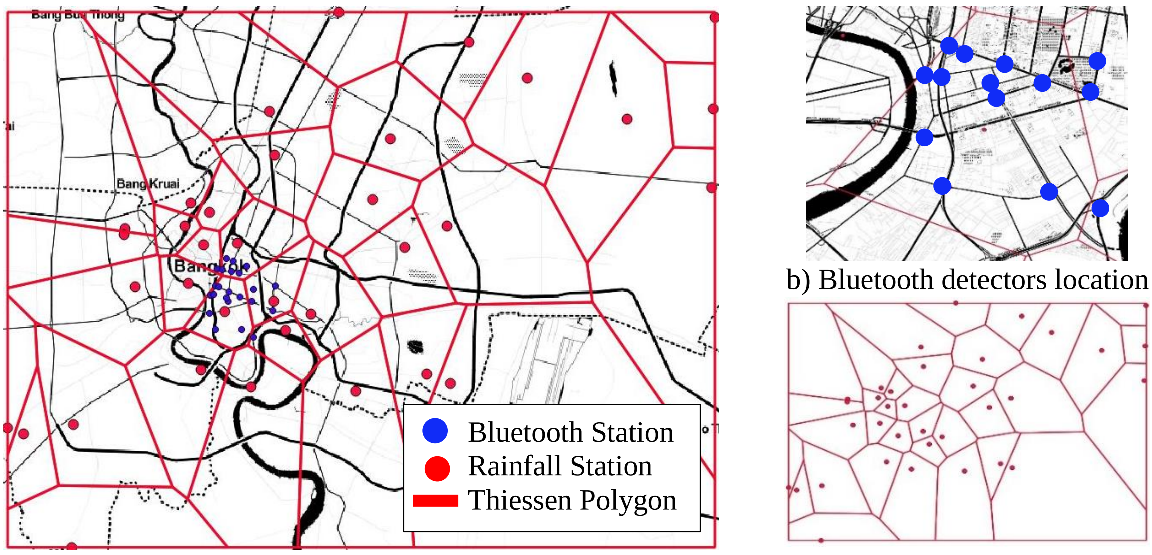
Currently, Bluetooth traffic monitoring is the most popular method for dynamic traffic data collection (Ayodele, 2017; Barceló Bugeda, Montero Mercadé, Bullejos, Serch, & Carmona, 2012; Blogg, Semler, Hingorani, & Troutbeck, 2010; Hu, 2013). The data collected using Bluetooth sensors is similar to data collected from Automatic Vehicle Identification (AVI) systems using dedicated transponders (e.g. such as electronic toll tags) (Haas et al., 2001) However, the main advantage of using Bluetooth over other technologies is the reduction in the cost of data collection which ultimately leads to the creation of large traffic databases for transportation studies (Puckett & Vickich, 2010).

The purpose of this research is to analyze the rainfall intensity effect on traffic operation of the urban network by analyzing the change in the key parameters of MFD using traffic data obtained by Bluetooth sensors and rainfall data obtained from meteorological sensors. The data used in this study was collected from the central business district in Bangkok, Thailand during the period of January to April 2018. The MFD parameters are useful for assessing the performance of urban roads, especially in a city like Bangkok with relatively high annual rainfall intensity as compared to other cities across the world.

2. DATA COLLECTION AND EXTRACTION

2.1 The Research Location

This research is based on traffic data collected as a result of a collaborative project between Department of Civil Engineering, Chulalongkorn University and College of Science and Technology, Nihon University was collected during a time from January 15th–April 30th, 2018 in the Central Business District (CBD) of Bangkok.



a) Central Business District Bangkok

b) Bluetooth detectors location

c) Rainfall stations

Figure 1 Locations of Bluetooth detectors and Rainfall stations in Urban Bangkok

The traffic data used in this research was collected by Bluetooth detectors installed at 26 intersections in Urban Bangkok (blue points in Figure 1(b)) and the rainfall data was obtained using a total of 35 weather detectors deployed by Thai Meteorological Department (red points in Figure 1(a)). The duration of data collection is 105 days among which there were a total of 38 of rainy days and 67 non-rainy days.

2.2 Bluetooth data

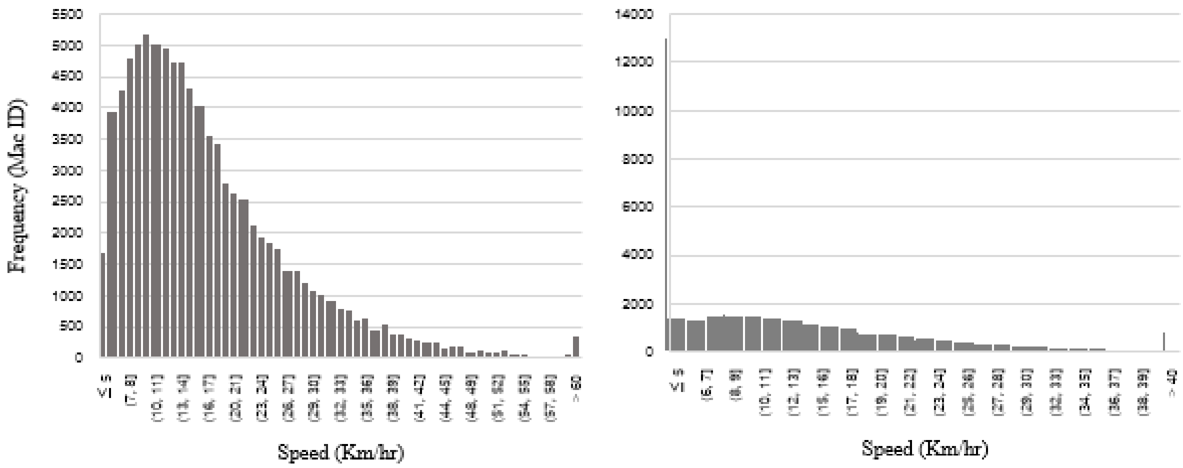
The traffic data consists of unique MAC addresses captured by the Bluetooth detectors and then registered with their corresponding details of date and time that allows us to calculate the time spent by each vehicle to pass between two intersections. Data gathered by Bluetooth sensors have some outliers that are cleaned before being used for travel time study (Khoei, 2014). The Median Absolute Deviation (MAD) technique is applied for removing outliers (Smith & Demetsky, 1994). This method defines upper Bound (UB) and lower Bound (LB) from the sample median and the mean absolute deviation from the median (MAD). The samples larger than the UB or smaller than LB are considered as outliers. The UB and LB are computed as

$$(UB, LB) = median \pm \sigma f \tag{1}$$

Where,

σ is the standard deviation from the MAD, $\sigma = 1.4826 \times MAD$

$f = 2$, as chosen as suggested in (Kieu, Bhaskar, & Chung, 2012).



a) Speed distribution in non-rainy days b) Speed distribution in rainy days

Figure 2 Speed distribution in Urban Bangkok

After calculating travel time values for each link in the road network, the data is filtered by the MAD method. Rest of the outliers are calculated based on the speed of each link. Figure 2 shows the speed distribution in urban Bangkok.

2.3 Rainfall Data

The rainfall data was obtained by collecting rainfall data from the various rain gauge measurements in the area studied. Location of rainfall stations (Figure 1(c)) is accurately mapped using the coordinates and the associated rainfall data is then interpolated using the

Thiessen polygon proposed in (Thiessen, 1911). Thiessen polygon is the most common method used in Hydrometeorology for determining average precipitation over an area when there is more than one measurement. The basic concept is to divide the watershed into several polygons, each one around a measurement point, and then take a weighted average of the measurements based on the size of each polygon. The model can be expressed mathematically as follows:

$$\bar{P} = \frac{P_1A_1+P_2A_2+P_3A_3+\ldots+P_nA_n}{A_1+A_2+A_3+\ldots+A_n} = \frac{\sum_{i=1}^{n} P_iA_i}{\sum_{i=1}^{n} A_i} \tag{2}$$

Where,

$\bar{P}$: average rainfall over an area

P_i: rainfall observed at the i^{th} station inside or outside the basin

A_i: area of the polygon surrounding the i^{th} station

n: number of areas

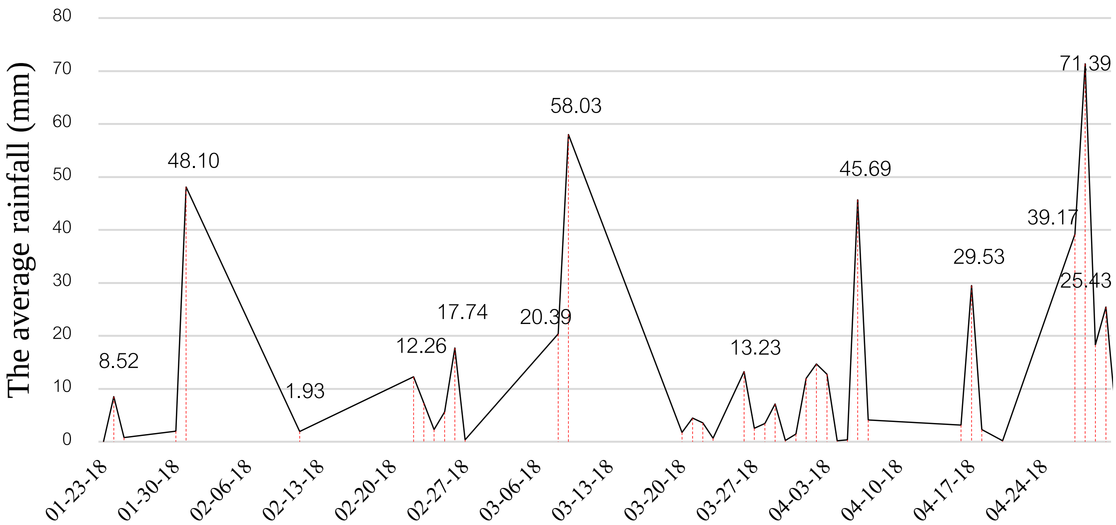


Figure 3 The average rainfall using the Thiessen Polygon

Thiessen method defines the boundary of Thiessen polygon for each contributing rainfall measuring station as shown in Figure 1. The calculation for average rainfall in urban Bangkok was performed for 38 rainy days between January 2018 to April 2018 as shown in Figure 3. It was found that light rain (0.1 mm to 10.0 mm) is most prevalent followed by moderate rain (10.1 mm to 90.0). The intensity classifications are according to the Thai Department of Meteorology.

3. METHODOLOGY

3.1 Macroscopic Fundamental Diagram

The idea of the Macroscopic Fundamental Diagram (MFD) was developed to establish a relationship between volume, speed, and density (Greenshields, Channing, & Miller, 1935). The number of MFDs indicates the existence of different levels of service on different network routes. The shape of the MFD generally depends on the network topology, traffic flow, rate of incoming traffic, peak/off-peak period, vehicle route choice, the signal timing plans of the intersections, and the infrastructure characteristics (Geroliminis & Boyacı, 2012; Geroliminis & Sun, 2011). The field was experimental in Yokohama, Japan (Daganzo & Geroliminis, 2008) defined as the relationship between network 'production', the weighted sum of flows of all links, and 'accumulation', the weighted sum of link densities. In this research, the section flows are measured at the downstream stop line of sections and aggregated 0-1 hour (every 5 minutes). The area of weighted flow (q^w), weighted density (k^w), and accumulation (n) are then calculated by averaging section variables across an area, according to the following definitions:

$$q^W = \sum_i q_i l_1 / \sum_i l_i \ , \ k^W = \sum_i k_i l_1 / \sum_i l_i \ , \ n = \sum_i k_i l_1 \tag{3}$$

where,

q_i : the traffic volume at the road section i .
k_i : the density at the road section i .
l_i : the length of the road section i

3.2 T-test method

The t-test is used to compare the means of two related samples (pair of values). In this study, the paired t-test can be used as the 2 sets of values being compared are related. We have a set of production under rainfall and non-rainfall conditions from the same observation road sections on the same day and time period. To compare the means of the two paired sets of data, the differences between all pairs must be first calculated. Let D represents the differences between all pairs. The average of the difference D is compared to 0. If there is any significant difference between the two pairs of samples, then the mean of D is expected to be far from 0. T-test statistics value can be calculated as follow:

$$t = \frac{\bar{D}}{s/\sqrt{n}} \tag{4}$$

where,

$\bar{D}$: the mean of the difference (D)
s: the standard deviation of the difference (D)
n: the size of D

The t value is read in t-test table the critical value of Student's t distribution corresponding to the significance level alpha (5%) as computing a 95% confidence interval. The degrees of freedom (df) used in this test are: df=n−1, indicating a significant difference between the means at the 0.05 level.

4. RESULTS AND DISCUSSION

The prior to investigation of the effects of rainfall on MFD's key parameters, the weather conditions are divided into 2 situations, namely, dry condition and rainfall condition, without considering the rain intensity categories, which results show the weighted flow, weighted speed, and weighted density obviously influenced by a rainy day, the average value reduced by 4.15 %, 5.01%, and 3.16% respectively. Under different rainfall categories, these parameters reduction vary according to the precipitation densities, as shown in Table 1.

Table 1. Flow-density- Speed data Statistics for Non-rainy and rainfall conditions

Weather Categories	Weighted flow (MAC id/hr.)		Weighted speed (km/hr.)		Weighted density (MAC id/km)	
	value	Change (%)	value	Change (%)	value	Change (%)
Non-rainy	20.82	Na	12.28	Na	2.13	Na
Rainy (all day)	20.73	-5.01	11.77	-4.15	2.19	-3.16
Rainy (light)	20.68	-0.67	12.06	-1.83	2.07	-3.04
Rainy (Moderate)	16.73	-19.63	11.99	-2.62	1.44	-32.52
p-value (all day)	0.0007124		0.007543		0.1416	
significant or not	Y		Y		N	

**Significance at the 0.05 level

From the results of t-test can be summarized that the rain has a noticeable negative effect on weighted flow and weighted speed of the road network. But there is no significant impacts on weighted density on urban roads. As shown in Figure.4 is the relationship model between weighted flow, weighted speed, and weighted density of urban road network in Bangkok under non-rainy and rainy conditions.

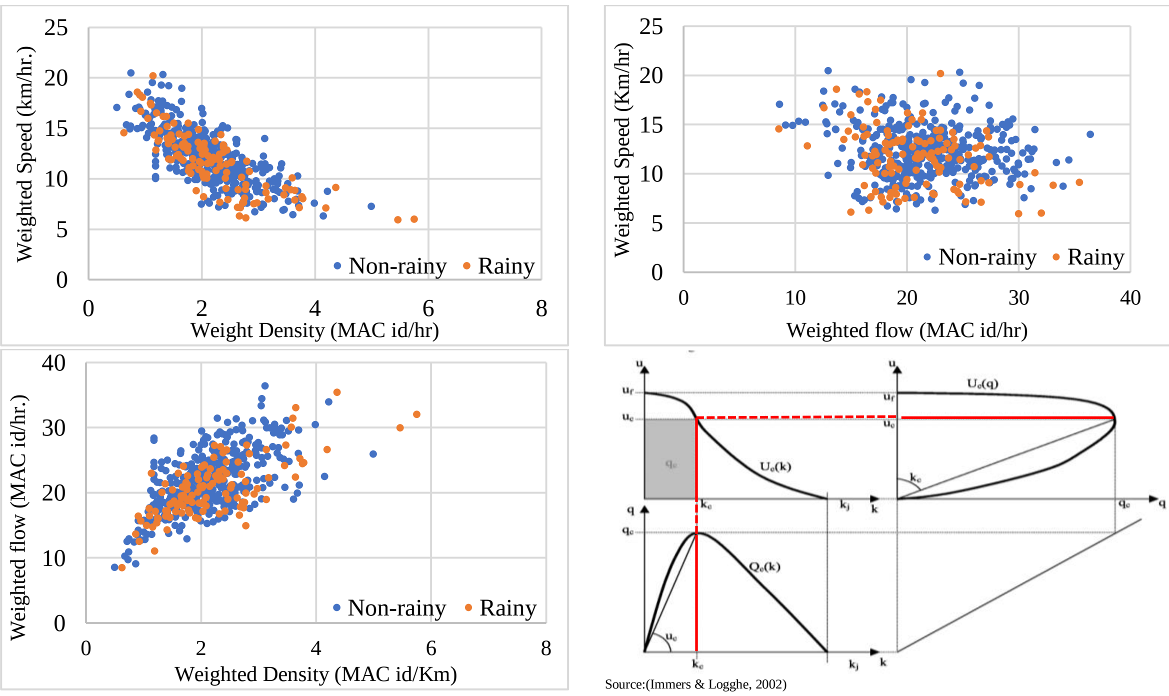


Figure 4 The relationship between macroscopic weighted for each condition

These relationships under rainfall conditions can be obtained through analyzing and fitting parameters by adopting Greenshields regression equations (Greenshields et al., 1935), including free-flow speed, the speed at capacity, and capacity under both dry and rain conditions. The fitting results of the key traffic-flow parameters are presented in Table 2.

Table 2 Regression analysis by weighted density- weighted speed relationship

Conditions	linear equation relationship	R^2	k_c (id/km)	q_c (id/hr)	u_c (km/hr)	k_j (id/km)	u_f (km/h)
Non-rainy	$u=18.377-2.869k$	0.54	3.20	29.42	9.19	6.40	18.377
Rainy (all day)	$u=17.661-2.687k$	0.63	3.31	29.21	8.83	6.61	17.661
Rainy (light rain)	$u=17.147-2.288k$	0.50	3.74	32.10	8.57	7.49	17.147
Rainy (Moderate)	$u=16.102-1.419k$	0.51	5.67	45.65	8.05	11.34	16.102

Consider speed-density relationship is a linear equation (Johnnie Ben-Edigbe & Ferguson, 2005; J Ben-Edigbe & Ferguson, 2009)can be computed critical density (k_c), maximum flow (q_c), critical speed (u_c), Jam Density (k_j) and Free Flow Speed (u_f) as shown in Table 2, all predicted values decreased as the intensity of rain increased. The findings in Table 2 can provide guidance for the management and model calibration of urban traffic in rainfall weather.

5. CONCLUSIONS

This study has confirmed the existence of the Macroscopic Fundamental Diagram (MFD) with a real data set of the signalized arterial network in urban Bangkok. The results show MFD's key parameters (Weighted flow, Weighted speed, and Weighted density) of the network is changed by the rain conditions, rainfall irrespective of their intensities have an impact on the average value reduced by 5.01%, 4.15%, and 3.16% respectively, and the results of t-test showed that rainfall condition has no significant impacts on weighted density on urban roads. When considering the increasing intensity of rainfall has caused a reduction to weighted flow and weighted density up to 19.63% and 32.52 % respectively, but weighted speed is slightly reduced to intensity due to the average speed in the urban area is already low. The result findings could provide insights into the impacts of rainfall intensity on urban road traffic for modeling their impacts on road users' route choice behavior.

Further research by concentric zoning will be better understanding and monitoring of the network conditions under rain conditions within the zone and identifying the areas for area-wide control purposes as some important features of radial networks with few connections between the corridors.

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