〔原著論文：審査付〕

Impact of Rainfall Intensity on Macroscopic Traffic Variables of Urban Roads Using Data from Bluetooth Detectors

Piyapong SUWANNO
Graduate School of Science and Technology, Nihon University
Prasan JITPAT
Rajamangala University of Technology Srivijaya
Rattanaporn KASEMSRI
School of Civil Engineering, Suranaree University of Technology
Atsushi FUKUDA
College of Science and Technology, Nihon University
Bethala ADITYA
College of Science and Technology, Nihon University

Abstract: The impact of rainfall intensity on the traffic volume of different links in the Bangkok road network was investigated using traffic data obtained from Bluetooth detectors placed at intersections. A macroscopic fundamental diagram (MFD) was used to compare the performance of the remaining (degraded) network across the various city road links in conditions of no rain, light rain, moderate rain, and heavy rain. Results of the MFD parameters, namely the free-flow speed and maximum capacity value were applied to volume-delay functions to measure network-wide traffic performance. Heavy rain increased total travel time in the network by 128 %, while average speed decreased by 41.17%. Results confirmed that rainfall intensity had a significant impact on traffic flow characteristics of an urban road network.
Keywords: *MFD, Rainfall condition, Bluetooth detector, VHT and VDT*

1. Introduction

Bangkok is the capital city of Thailand with a population of around 8 million people and the center for all activities in the country. The city is frequently impacted by flooding the most recent severe flood event was in 2011 because of the poor drainage system, causing many transportation problems to public. Heavy rainfall interrupts and delays all types of travel modes. Motorized vehicles have to reduce speed due to lack of visibility and this causes traffic congestion. Roads in low-lying areas often become impassable, forcing drivers to take alternative routes to reach their destinations. Decrease in speed and the resultant increase in travel length lead to higher fuel consumption, which impacts the environment through greater emission of exhaust gases. It is important to comprehensively understand the impact of rainfall on the transportation system before proposing a method for better traffic management in Bangkok. Copious research has addressed the relationship between traffic and rainfall. The negative correlation between traffic volume and amount of rainfall was investigated by using mathematical equations (e.g., Unrau and Andrey (2006), Rakha, et al. (2008), Billot, et al. (2019))[1-3].

Here, a macroscopic fundamental diagram (MFD) was employed to better comprehend traffic flow characteristics vs rainfall. MFD relationships between flow and density, density and speed, and speed and flow were studied concerning traffic parameters in a complex urban network (e.g., Geroliminis and Daganzo (2007), Daganzo and Geroliminis (2008), Geroliminis and Carlos (2008))[4-6]. Xu, et al. (2013)[7] studied the impact of rainfall on road networks using MFD. Collecting traffic data using traditional methods requires extensive manpower and time.

Nowadays, innovative technologies are utilized to collect dynamic traffic data, with Bluetooth one of the most popular (e.g., Blogg, et al. (2010), Barceló, et al. (2012), Hu (2013), Ayodele (2017))[8-11]. The main advantage of using Bluetooth over other technologies is the cost reduction of data collection that ultimately leads to the creation of large traffic databases for transportation studies (Puckett and Vickich (2010))[12].

The impact of rainfall on traffic operation in an urban network was assessed by analyzing changes in key parameters of MFD. Traffic data were obtained using Bluetooth detectors, and suitable travel models were developed according to different rainfall scenarios to evaluate the performance of the remaining (degraded) network. Results can be applied to improve traffic flow and reduce disruption during heavy rainfall by providing timeous information to the public through tools such as variable message signals, local radio and television. This will enable selection of more appropriate routes, cancellation of unnecessary trips or changes in modes of travel.

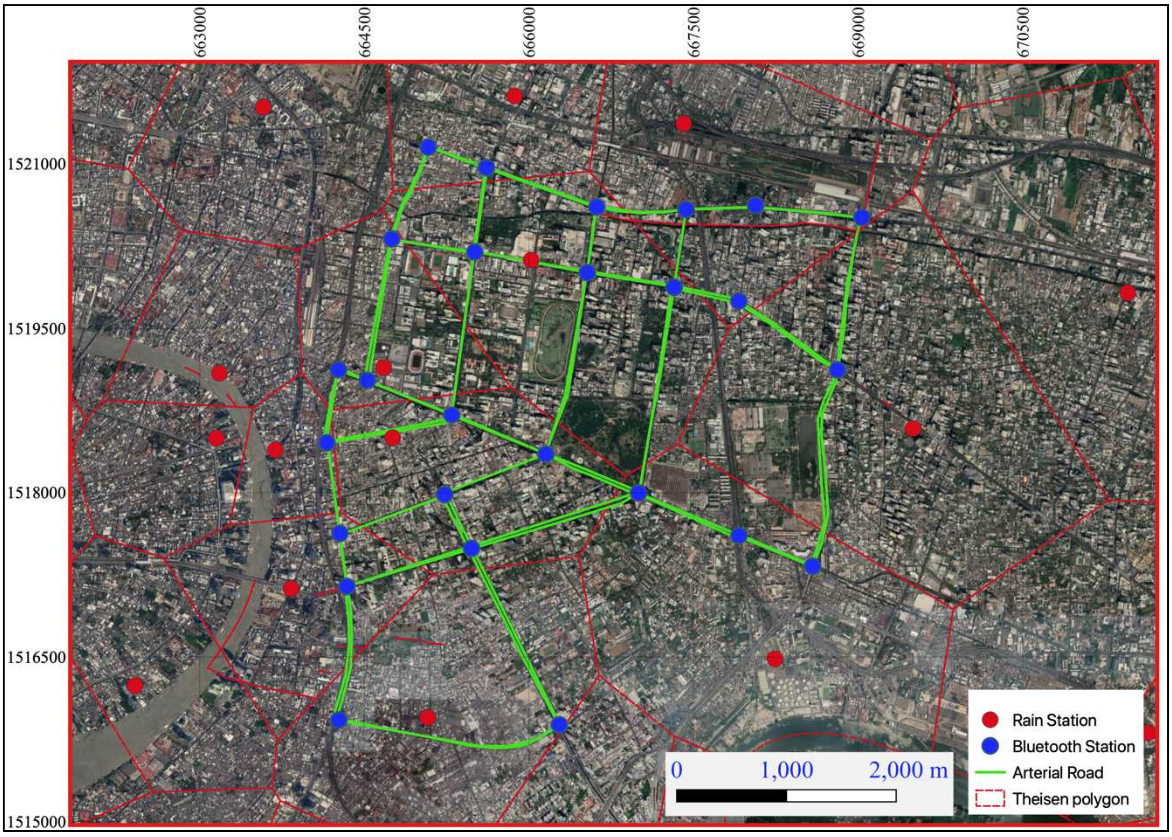


Figure 1. Locations of Bluetooth detectors and rainfall stations in urban Bangkok

2. Data collection and extraction

2-1 Research location

The study pertains to part of the Central Business District (CBD) of Bangkok covering an area of about 36 km^2.

Traffic data, including speed, density and volume were retrieved from Bluetooth detectors installed at 26 intersections in Figure 1 (Blue circle) on arterial roads between January 15th and April 30th, 2018. This was a collaboration project between the Department of Civil Engineering, Chulalongkorn University and the College of Science and Technology, Nihon University. The Bluetooth detectors scanned and read the Media Access Control (MAC) address of active Bluetooth devices within range.

The MAC address is a unique, anonymous identifier assigned to each Bluetooth device. If the same MAC address is found in different detectors, the difference in timestamps gives the travel time between the two locations. In this way, the uniqueness of the MAC address makes it possible to track the devices throughout the transport network.

Bluetooth detectors have a particular range of communication depending on the power of the Bluetooth radio transmitter device, normally about a 100-meter radius. Data including incidents were deleted to isolate their impact. Weekend and holiday traffic were also excluded since these travel patterns were significantly different from those of weekdays.

Rainfall data is collected from 135 rainfall stations in Bangkok by the Thai Meteorological Department. However, significant variance occurs between these rainfall stations, indicating that rainfall is a local phenomenon in Urban Bangkok, and may vary significantly over a small geographic area. Therefore, the radius of a buffer area R around each rainfall station was determined to increase the accuracy of using the rainfall detected by each measurement station to represent that of the segment. The distance R was selected as 3 km. from previous research (e.g., Agarwal, et al. (2005), Tsapakis, et al. (2013), Hu, et al. (2018))[13-15]. This study considered 35 rainfall stations in Figure 1 (Red circle) to calculate the average rainfall. The duration of data collection was 105 days. During this period there were 38 rainy days and 67 non-rainy days.

2-2 Bluetooth data

Bluetooth data were stored in the main server and exported in a CSV file by date, as shown in Table 1. Bluetooth data consisted of a unique MAC address (column V3) captured by Bluetooth detectors (column V7) installed inside the police box at main road intersections. The detectors registered the corresponding details of date and time (column V5) that allowed calculation of the time taken by each vehicle to pass between two intersections.

Table 1. Example of raw data from database server

V1	V2	V3	V4	V5	V6	V7
1531153122	-	94:D0:29:38:D8:0E	-70	2018-01-14 00:00:00.75	2018-01-14 00:00:08.00	215
1531153123	-	94:D0:29:38: D8:0E	-55	2018-01-14 00:00:03.90	2018-01-14 00:00:08.00	215
1531153124	-	94:D0:29:38:D8:0E	-68	2018-01-14 00:00:04.84	2018-01-14 00:00:08.00	215
1531153125	-	94:D0:29:38:D8:0E	-66	2018-01-14 00:00:05.16	2018-01-14 00:00:08.00	215
1531153126	-	94:D0:29:38:D8:0E	-64	2018-01-14 00:00:05.88	2018-01-14 00:00:08.00	215
1531153127	-	94:D0:29:38:D8:0E	-54	2018-01-14 00:00:07.160	2018-01-14 00:00:08.00	215

Data gathered by the sensors were cleaned to remove outliers before input to the travel time study[16]. Speed is one criterion used to examine outliers, while Bluetooth data consisted of unique MAC addresses captured by the detectors. Data were registered with the corresponding details of date and time to allow calculation of the speed of each vehicle passing between two intersections in the field site study area in Figure 1. The distance of each road segment (link) was also measured.

Figure 2 shows speed distribution on the road segment, with one outlier record of over one thousand km./hr. This outlier occurred due to inaccuracy of the technology as a timestamp detection error that led to an excessively short travel time of one second between travel paths.

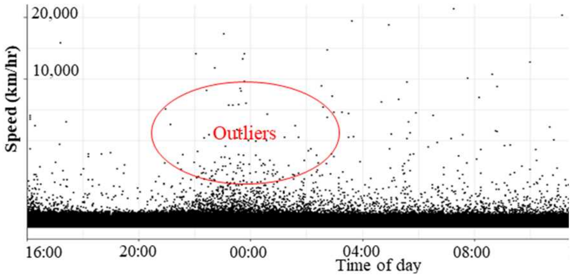


Figure 2. Example of speed distribution on road segment

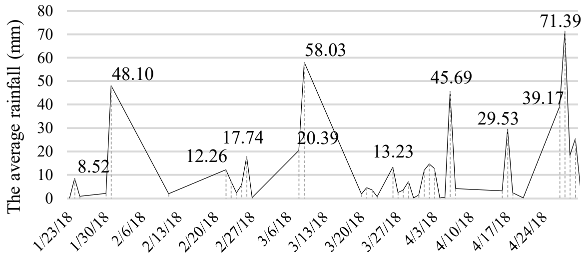


Figure 3. Average rainfall using Thiessen polygons

The median absolute deviation (MAD) technique was applied to remove the outliers following Smith and Demetsky (1994)[17]. This method defines upper bound (UB) and lower bound (LB) from the sample median and the mean absolute deviation from the median (MAD). Samples larger than the UB or smaller than the LB were considered as outliers. The UB and LB were computed as Equation (1).

$$(UB, LB) = median \pm \sigma f \quad (1)$$

where

σ: Standard deviation from the MAD, $\sigma = 1.4826 \times MAD$.

f: 2[18].

2-3 Rainfall data

Rainfall data were obtained from the various rain gauges situated in the study area. Locations of rainfall stations (Figure1) were accurately mapped using coordinates and associated rainfall data were then interpolated using Thiessen polygons[19]. Thiessen polygons are most commonly used in hydrometeorology to determine 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. Calculation of average rainfall in urban Bangkok was performed for 38 rainy days between January 2018 to April 2018 and shown in Figure 3. Rainfall was classified as light rain (0.1 to 10.0 mm), moderate rain (10.1 to 35.0 mm) and heavy rain (35.1 to 90 mm). Intensity classifications followed the Thai Meteorological Department.

3. Research methodology

MFD parameters were initially computed for different rainfall conditions as previously described. Subsequently, diverse forms of the fundamental traffic equation were utilized to analyze the data and develop traffic models that characterized the behavior of critical traffic variables as a function of rainfall conditions.

3-1 Macroscopic fundamental diagram (MFD)

The MFD concept was developed to establish a relationship between volume, speed, and density[20]. The number of MFDs indicates the existence of different levels of service on different network routes. The shape of the MFD generally depends on network topology, traffic flow, rate of incoming traffic, peak/off-peak period, vehicle route choice, signal timing plans of the intersections, and infrastructure characteristics[21-22]. The experimental field in Yokohama[5] was defined as the relationship between network 'production' as the average sum of the flows of all links, and network 'accumulation' as the average sum of link densities. Here, the section flows were measured at the downstream stop line of sections and aggregated 0-1 hour (every 5 minutes). The area of average flow (q^W), average density (k^W), and accumulation (n) were then calculated by averaging section variables across an area according to the following definitions:

$$q^W = \sum_i q_i l_i / \sum_i l_i \quad (2)$$

$$k^W = \sum_i k_i l_i / \sum_i l_i \quad (3)$$

$$n = \sum_i k_i l_1 \quad (4)$$

where

q_i: The traffic flow 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* could be used as the two sets of values being compared were related. Production sets under rainfall and no rainfall conditions were available from the same observation road sections on the same day and time period[7]. To compare the means of the two paired sets of data, the differences between all pairs must be first calculated. Let D represent the differences between all pairs. The average of the difference D is compared to zero. If there is any significant difference between the two pairs of samples, then the mean of D is expected to be far from zero. The t-test statistics value was calculated as follows:

$$t = \frac{\bar{D}}{s/\sqrt{n}} \tag{5}$$

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

3-3 Road network model

Estimating both spatial and temporal distribution of traffic demand is critical when considering traffic flow under different rainfall conditions. In this study, the subarea network (Bluetooth area) was extracted from a regional demand model as the Extended Bangkok Urban Model (eBUM) designed by the Office of Transport and Traffic Policy and Planning (OTP)[23]. The eBUM model passed process calibration and validation and was determined as reliable to forecast travel volume in various situations.

The eBUM model passed process calibration and validation and was determined as reliable to forecast travel volume in various situations. Model attributes were then imported into a scenario as a new database. The matrix resulting from the traversal assignment was also imported into the new database and used as the demand assigned in the subarea scenario to perform the requisite adjustments. The subarea model consisted of 294 links and connectors, 172 major intersections and 70 zones, as shown in Figure 4.

A stochastic user equilibrium (SUE)[24] procedure was applied to the choice of route between an origin and a destination. The perceived path travel time along any given path was normally distributed with a mean equal to the actual (measured) travel time. Relationships between the distribution of perceived travel times over links and paths were utilized in the derivation of a Probit-based stochastic network loading algorithm[25]. The formulae used during the equilibrium calculations to link the performance functions were developed at the U.S. Bureau of Public Roads (BPR)[26].

To investigate the effect of rainfall on time, speed and assigned traffic volume, we revised the BPR function with γ and δ values as link performance parameters to adjust free-flow speed and capacity on links according to rainfall conditions. The function used in this study is shown in Equation (6).

$$t_a = \frac{60L_a}{\gamma u_{f_a}}\left(1 + \alpha\left(\frac{x_a}{\delta c_a}\right)^{\beta}\right) \tag{6}$$

where

t_a: The travel time on link *a*.

x_a: The flow on link *a*.

u_{f_a}: The free-flow speed on link *a*.

L_a: The length on link *a*.

c_a: The "practical capacity" of link *a*.

α: The model parameter (0.15[23]).

β: The model parameter (4.0[23]).

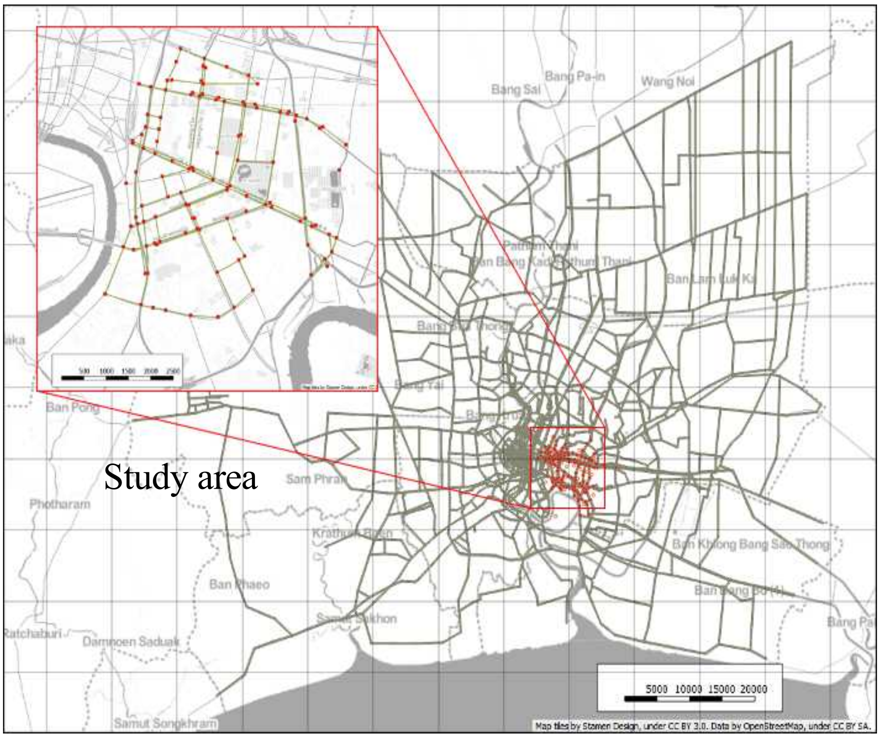


Figure 4. Extended Bangkok urban model

4. Results and discussion

Different rainfall conditions were investigated for key parameters of the MFD that varied according to precipitation densities, as shown in Table 2.

Table 2. Flow density and speed data statistics for no rain and rain conditions

Condition	Average flow (veh/hr.)		Average speed (km./hr.)		Average density (veh/km)	
	value	change (%)	value	change (%)	value	change (%)
No rain (Normal)	103	N/A	15	N/A	31	N/A
Light rain	104	-0.9	14	-6.67	33	-6.06
Moderate rain	96	-6.7	11	-26.67	38	-22.58
Heavy rain	75	-27.18	7	-53.33	45	-45.1
p-value/significant or not	0.00/Y		0.00/Y		0.00/Y	

The results of the t-test showed that rainfall had a significant negative effect on average flow, average density, and average speed of the road network. Figure 5 shows the traffic relationships of the urban road network in Bangkok under no rain and rain conditions.

The MFD shape shows the change in traffic operation of the network. Varying degrees of rainfall make the MFD shape change and scatter occurs. By comparison, the no rain scenario shows different degrees of impact on the stability and certainty of the road network. Fitting MFD curves for each condition are shown in Figure 6. Negative effects increased with the severity of rain conditions. Equations of fitting MFD curves under each rain condition are presented and shown in Table 3, as similar to the Greenshields model[26] of link traffic. The fitting curves obtained utilized many key parameters to quantitatively master and evaluate the traffic flow of the study network. The equations were obtained by analyzing and fitting the parameters of Greenshields[20] such as free-flow speed (u_f), maximum flow (q_c) and traffic jam density (k_j). Results of the key traffic-flow parameters are presented in Table 4. The coefficient of determination R^2 is a statistic that provides information about the goodness of model fit, and can be used to describe discrete changes in the MFD. We found that the R^2 value reduced as rainfall increased, while continuity also decreased.

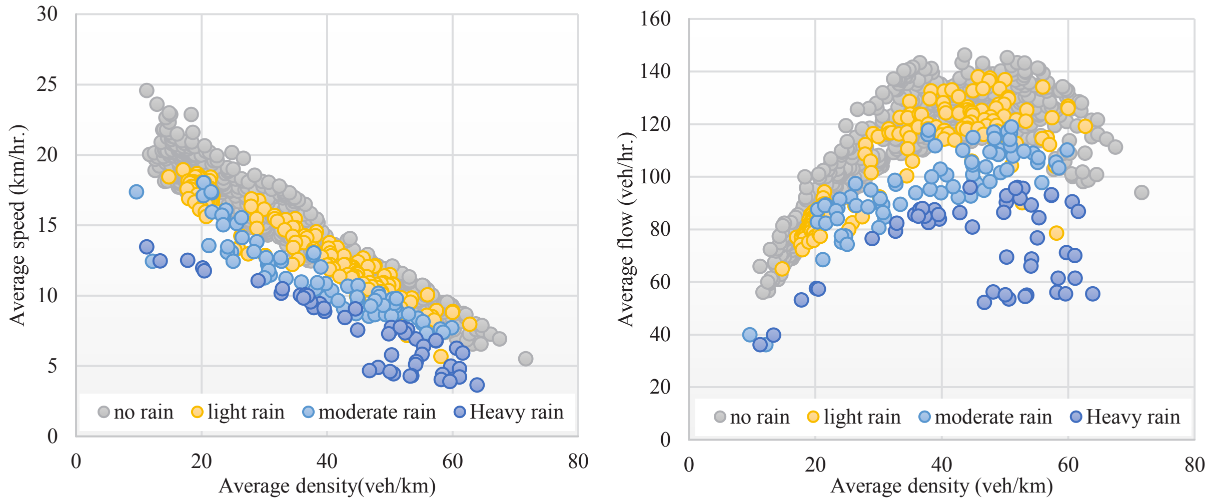


Figure 5. MFD for different rain conditions

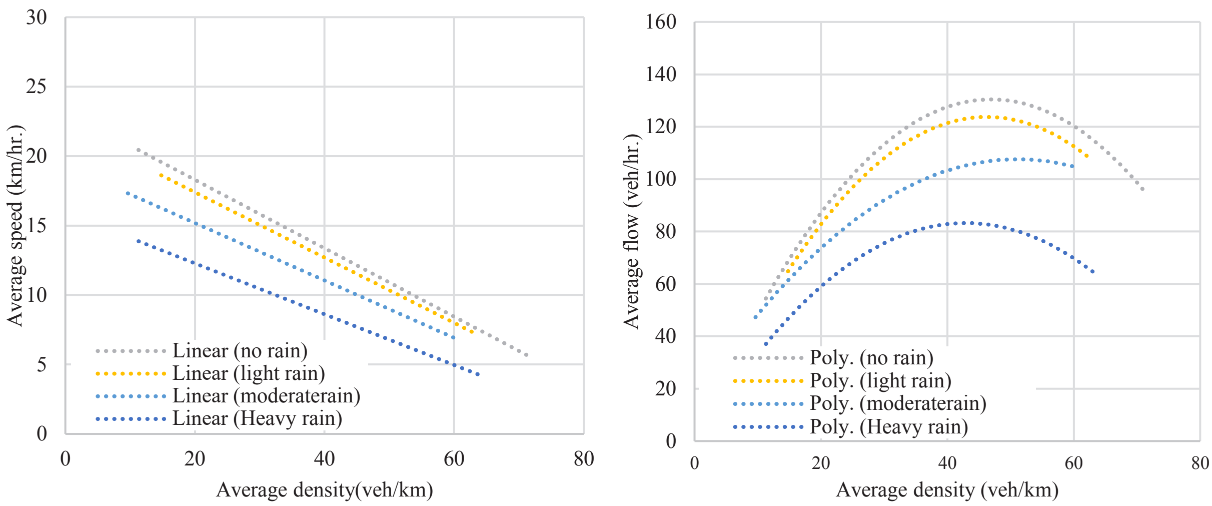


Figure 6. Fitting MFD curves for different rain conditions

Table 3. Regression analysis by of macroscopic traffic variables

Condition	Equation relationships			
	Average density Average speed	R^2	Average density Average flow	R^2
Normal	$y= -0.246x+23.23$	0.92	$y= -0.059x^2+5.609x-01.26$	0.90
Light rain	$y= -0.235x+22.09$	0.92	$y= -0.059x^2+5.504x-03.60$	0.85
Moderate rain	$y= -0.207x+19.31$	0.82	$y= -0.035x^2+3.591x+15.90$	0.75
Heavy rain	$y= -0.183x+15.94$	0.83	$y= -0.046x^2+3.959x-01.76$	0.50

Table 4. Results of fitting macroscopic traffic variable equations

Condition	Free-flow speed (km/hr.)		Jam density (veh/km)		Maximum flow (veh/hr.)	
	value	change (%)	value	change (%)	value	change (%)
Normal	23.22	-	94.00	-	130.00	-
Light rain	22.09	-4.84	94.00	0.00	124.00	-4.62
Moderate rain	19.31	-16.82	93.00	-1.06	107.00	-17.70
Heavy rain	15.92	-31.44	87.00	-7.45	83.00	-36.15

Period demand estimates were used to apply the speed-density relationship as a linear equation[27-28] to a real road. This was computed to evaluate the full impacts of the performance of the remaining (degraded) network due to rain. Volume-delay functions were applied to the performance of the remaining parameters based on the corresponding road conditions during rain, as shown in Table 5.

Table 5. Volume-delay functions

Condition	Free-flow speed parameter (γ)	Capacity parameter (δ)	Function
Light rain	0.95	0.95	$t_a = \frac{60L_a}{0.95u_{f_a}}\left(1 + 0.15\left(\frac{x_a}{0.95c_a}\right)^4\right)$
Moderate rain	0.81	0.82	$t_a = \frac{60L_a}{0.81u_{f_a}}\left(1 + 0.15\left(\frac{x_a}{0.82c_a}\right)^4\right)$
Heavy rain	0.84	0.64	$t_a = \frac{60L_a}{0.84u_{f_a}}\left(1 + 0.15\left(\frac{x_a}{0.64c_a}\right)^4\right)$

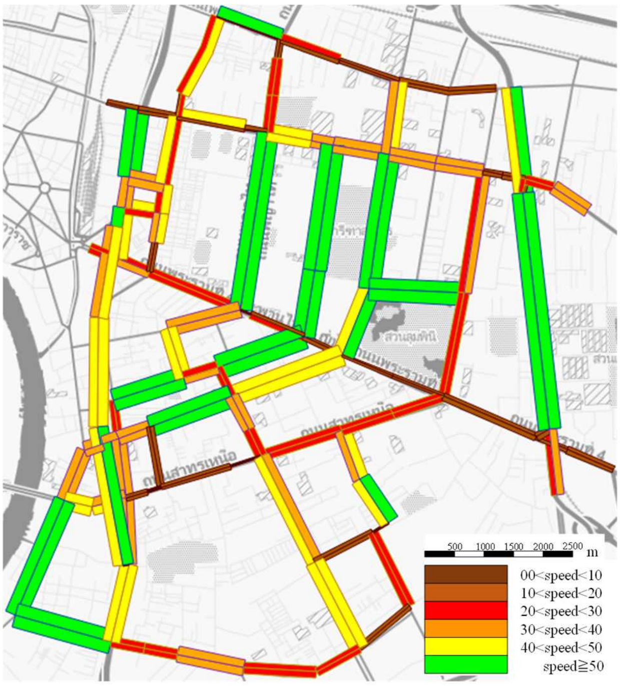
Table 6 summarizes the network-wide traffic performance. Overall, traffic congestion increased during rainfall. Average speed decreased from 30.77 km/hr. (no rain scenario) to 18.30 km/hr. (normal scenario), a decrease of 41.17%. Vehicle hours traveled (VHT) increased by 8.17%, 36.56% and 128%, respectively while maximum total travel time in the network almost tripled from the base case scenario. Vehicle distance traveled (VDT) showed a slight increase of 0.62%, 3.36%, and 4.54% with respect to the base case scenario.

Table 6. Network performance measure comparison

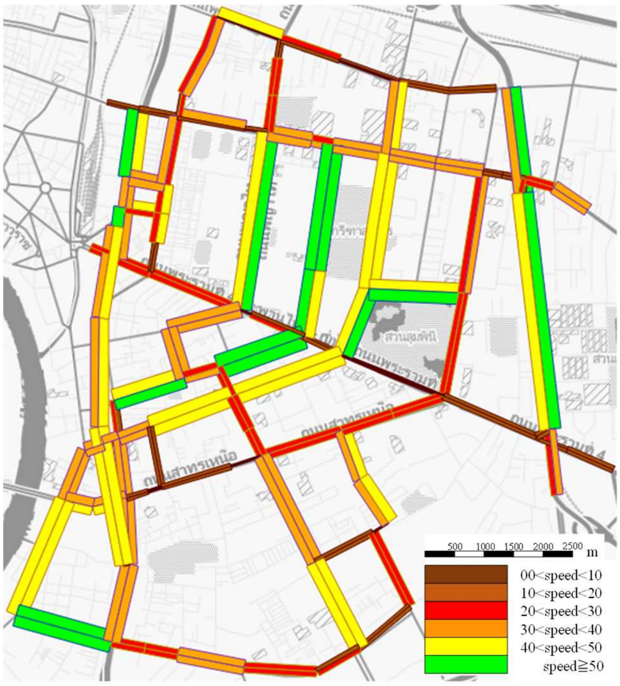
Performance measure	Normal	Light rain		Moderate rain		Heavy rain	
	value	value	change (%)	value	change (%)	value	change (%)
Average speed (km/hr.)	30.77	28.97	-7.34	24.42.00	-25.70	18.10	-41.17
VDT (veh-km)	163530.00	164174.00	0.40	166153.00	1.60	169466.00	3.63
VHT (veh-hr.)	7795.00	8432.00	8.17	10645.00	36.56	17837.00	128.00

All the links shown in the network (Figure 7) are two-way arterial roads. Multicolor plots of speed variation compare both normal and rainfall scenarios. Traffic speed was divided into six service levels. Level 1, shown by brown color, represents the worst quality of traffic flow with vehicle speed 0-10 km/hr. while level 6, shown by green color, represents the best quality of traffic flow with speed of 50 km/hr. and above.

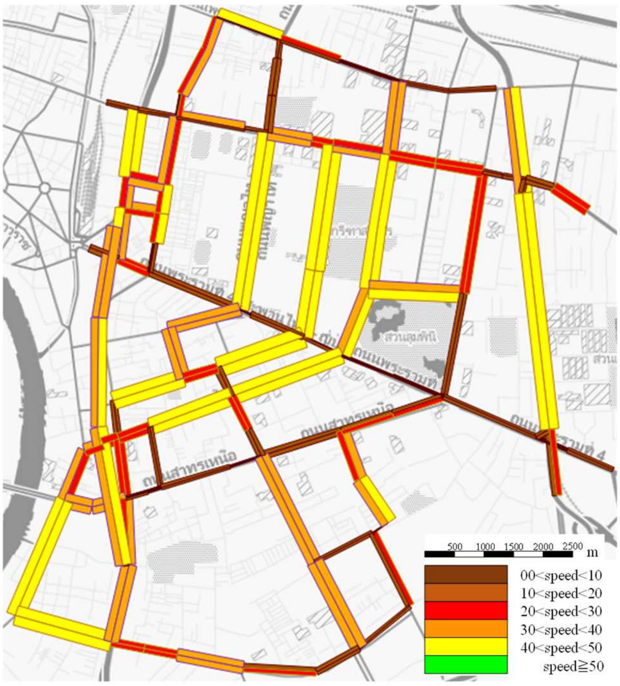
Vehicle speed was compared between normal day scenario (a) and rainy day scenario with different rainfall intensities as light (b), moderate (c) and heavy (d). Figure 7 shows that the speed of the network decreased during rainy days. During light rain days, vehicle speed was almost equal to a normal day as most of the links in the network showed speed at level 6, i.e., 50 km/hr. and greater. During moderate rain days, the maximum number of links were yellow, with vehicle speed decreased to level 3 at 30-40 km/hr. while at intersections speed decreased to 20-30 km/hr. During heavy rain, the network was almost grid-locked, with speed at less than 10 km/hr. and all the links represented as brown color.



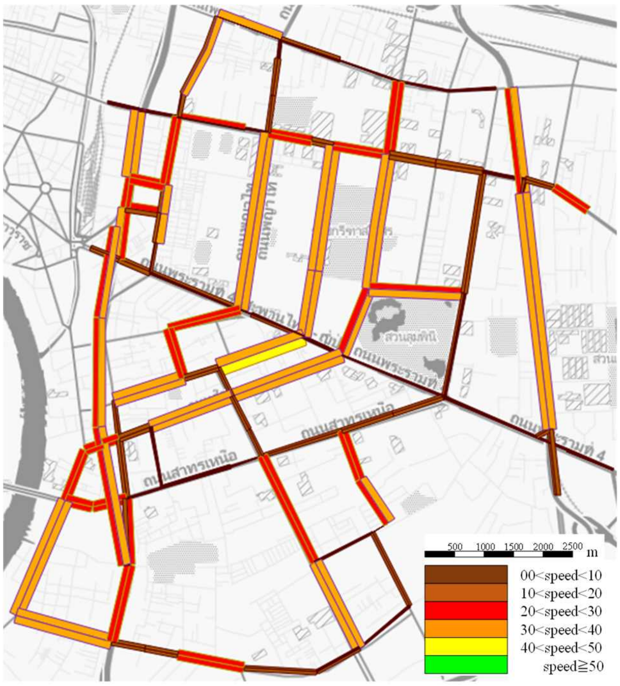
a) Normal scenario



b) Light rain scenario



c) Moderate rain scenario



d) Heavy rain scenario

Figure 7. Speed comparison each rain conditions

4. Conclusions

Results using macroscopic fundamental diagrams with real data were presented for a section of the signalized arterial network in urban Bangkok. MFD key parameters as average flow, average speed, and average density of the network were affected by light, moderate and heavy rainfall. Average reductions in speed, as shown by the traffic model, were 6.67%, 26.67% and 53.33%, respectively.

Increased rainfall intensity caused increases in VDT and VHT at 4.54% and 128%, respectively. People spent more time traveling during rainy days and amount of fuel consumption (vehicular emission) also increased accordingly during light, moderate and heavy rainfall days compared with non-rainy days.

Traffic in Bangkok is affected by rainfall. To deal with these conditions, planners require quality traffic management models. Traffic signals can be optimized using lane capacity and toll exemption during rainy days. Real time alternative routes can be suggested by Variable Message Signs (VMS) and other intelligent transportation systems to allow travelers to reach their destinations in time during rainy days.

References

1) Unrau, D. and Andrey, J. (2006): Driver Response to Rainfall on Urban Expressways, TRR, Vol.1980(1), pp.24-30

2) Rakha, H., Farzaneh, M., Arafeh, M. and Sterzin, E. (2008): Inclement Weather Impacts on Freeway Traffic Stream Behavior, TRR, Vol.2071(1), pp.8-18

3) Billot, R., El Faouzi, N.E. and De Vuyst, F. (2009): Multilevel Assessment of the Impact of Rain on Drivers' Behavior: Standardized Methodology and Empirical Analysis, TRR, Vol.2107(1), pp.134-142

4) Geroliminis, N. and Daganzo, C.F. (2007): Macroscopic Modeling of Traffic in Cities, TRB 86th Annual Meeting, No.07-0413

5) Daganzo, C.F. and Geroliminis, N. (2008): An Analytical Approximation for the Macroscopic Fundamental Diagram of Urban Traffic, TR Part B: Methodological, Vol.42(9), pp.771-781

6) Geroliminis, N. D., Carlos F. (2008): Existence of Urban-Scale Macroscopic Fundamental Diagrams: Some Experimental Findings, TR Part B: Methodological, Vol.42(9), pp759-770

7) Xu, F., He, Z., Sha, Z., Zhuang, L. and Sun, W. (2013): Assessing the Impact of Rainfall on Traffic Operation of Urban Road Network, Procedia-Social and Behavioral Sciences, Vol.96, pp.82-89

8) Blogg, M., Semler, C., Hingorani, M. and Troutbeck, R. (2010): Travel Time and Origin-Destination Data Collection using Bluetooth MAC Address Readers, ATRF, Vol.36

9) Barceló Bugeda, J., Montero Mercadé, L., Bullejos, M., Serch, O. and Carmona Bautista, C. (2012): Dynamic OD Matrix Estimation Exploiting Bluetooth Data in Urban Networks, Proceedings of the International Conference, pp.116-121

10) Hu, Y. (2013): Short-Term Prediction of Freeway Travel Times using Data from Bluetooth Detectors, Doctoral dissertation of University of Waterloo

11) Ayodele, E.G. (2017): Using Bluetooth to Estimate Traffic Metrics for Traffic Management Applications, Doctoral dissertation of Newcastle University

12) Puckett, D.D. and Vickich, M.J. (2010): Bluetooth-Based Travel Time/Speed Measuring Systems Development, University Transportation Center for Mobility, No. UTCM 09-00-17

13) Agarwal, M., Maze, T.H. and Souleyrette, R. (2005): Impacts of Weather on Urban Freeway Traffic Flow Characteristics and Facility Capacity, Proceedings of the 2005 mid-continent transportation research symposium, pp.18-19

14) Tsapakis, I., Cheng, T. and Bolbol, A. (2013): Impact of Weather Conditions on Macroscopic Urban Travel Times, Journal of Transport Geography, Vol.28, pp.204-211

15) Hu, S., Lin, H., Xie, K., Dai, J. and Qui, J. (2018): Impacts of Rain and Waterlogging on Traffic Speed and Volume on Urban Roads, 21st ITSC, pp.2943-2948

16) Khoei, A.M. (2014): Arterial Short Term Travel Time Prediction using Bluetooth Data, Doctoral dissertation of Queensland University of Technology

17) Smith, B.L. and Demetsky, M.J. (1994): Short Term Traffic Flow Prediction Models a Comparison of Neural Network and Nonparametric Regression Approaches, Proceedings of IEEE International Conference on Systems, Vol.2, pp.1706-1709

18) Kieu, L.M., Bhaskar, A. and Chung, E. (2012): Bus and Car Travel Time on Urban Networks: Integrating Bluetooth and Bus

Vehicle Identification Data, 25th ARRBC

19) Thiessen, A.H. (1911): Precipitation Averages for Large Areas. Monthly weather review, Vol.39(7), pp.1082-1089

20) Greenshields, B. D. (1935): A Study in Highway Capacity, Highway Research Board Proc, pp448-477

21) Geroliminis, N. and Sun, J. (2011): Properties of A Well-Defined Macroscopic Fundamental Diagram for Urban Traffic, TR Part B: Methodological, Vol.45(3), pp.605-617

22) Geroliminis, N., and Boyacı, B. (2012): The Effect of Variability of Urban Systems Characteristics in the Network Capacity, TR Part B: Methodological, Vol.46(10), pp1607-1623

23) OTP (Office of Transport and Traffic Policy and Planning) (2020): Results of Transport and Traffic Analysis, http://mistran.otp.go.th/mis/RoadAverage.aspx

24) Daskin, M. S. (1985): Urban Transportation Networks: Equilibrium Analysis with Mathematical Programming Methods by Yosef Sheffi, Transportation Science, Vol.19, No.4, pp463-466

25) Meng, Q., Lam, W.H. and Yang, L. (2008): General Stochastic User Equilibrium Traffic Assignment Problem with Link Capacity Constraints, Journal of Advanced Transportation, 42(4), pp429-465

26) Bureau of Public Roads (1964): Traffic Assignment Manual for Application with A Large, High Speed Computer, US Department of Commerce, Bureau of Public Roads, Office of Planning, Urban Planning Division, Vol.2

27) Ben-Edigbe, J. and Ferguson, N. (2005): Extent of Capacity Loss Resulting from Pavement Distress, Proceedings of the Institution of Civil Engineers-Transport, Vol.158, No.1, pp.27-32

28) Ben-Edigbe, J. and Ferguson, N. (2009): Qualitative Road Service Reduction Resulting from Pavement Distress, WIT International Conference on Urban Transport, pp.23-25

Acknowledgements

We thank Assoc.Prof. Sarawit Narupiti from Faculty of Engineering, Chulalongkorn University, Thailand for Bluetooth data and Thai Meteorological Department for rainfall data.

Corresponding Author

Prasan JITPAT

College of Industrial Technology and Management, Rajamangala University of technology Srivijaya University

99 M4, Khanom, Nokhon Si Thammarat, Thailand **80210

E-mail: prasan.j@rmutsv.ac.jp

Received: 4 August 2020 Accepted: 7 December 2020