

Macroscopic Fundamental Diagrams According to the Different Flood Depths on Probe Vehicle Data in Urban Bangkok

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Abstract: Impact of flood depth on traffic volume in two different zones of the Bangkok road network was investigated using traffic data obtained from probe vehicle trajectories. A Macroscopic Fundamental Diagram (MFD) was utilized to compare traffic flow rates across two road network zones in the city for a variety of flood depths, namely 0-5 cm, 5-10 cm, 10-15 cm, 15-30 cm, and more than 30 cm. Results of empirical analysis over an observation period of one year as 2019 showed that flood depths had a strong correlation with the MFD parameters of free-flow speed, maximum flow, and traffic jam density. In particular, road floods greatly reduced average maximum flow across the inner city road network in Bangkok. Road floods had a significant impact on traffic characteristics of urban road networks.

Key words: Road flood, probe vehicle, MFD.

1. Introduction

Nowadays, global warming has increased the frequency, duration, patterns, and intensity of extreme rainfall in many developing cities. Heavy rainfall or continuous precipitation as a percentage of total rainfall has also significantly increased. Rainfall is projected to increase by 9.65% from 2011 to 2099 [1]. With rapid urbanization, drainage systems have not been sufficiently developed, and their maintenance is often inadequate. In such a scenario, excessive rainfall results in road floods with immediate impact on the transport system.

On June 07, 2019 heavy precipitation in Bangkok

resulted in the flooding of 26 roads in 14 areas causing traffic congestion [2]. The impact of road floods on average vehicle speed is shown Fig. 1. The average speed during a normal rush hour is almost the same as the average speed when flood depth occurs at less than 10 cm. Thus, average speed of travel during rush hours is unaffected when the flood depth is less than 10 cm. Conversely, when the flood depth is more than 10 cm during rush hour, average traveling speed is reduced. It takes around 3 hours to drain the roads when rainfall intensity exceeds 5 mm/5 min. Research by Hilly et al. [3] investigated the impact of road waterlogging in the Sukhumvit area of Bangkok by interviewing motorcyclists, taxis, small pick-ups, and buses to identify the relationship between water depth and vehicle speed. Results showed that flooding at a depth of 30 cm and above caused traffic congestion in

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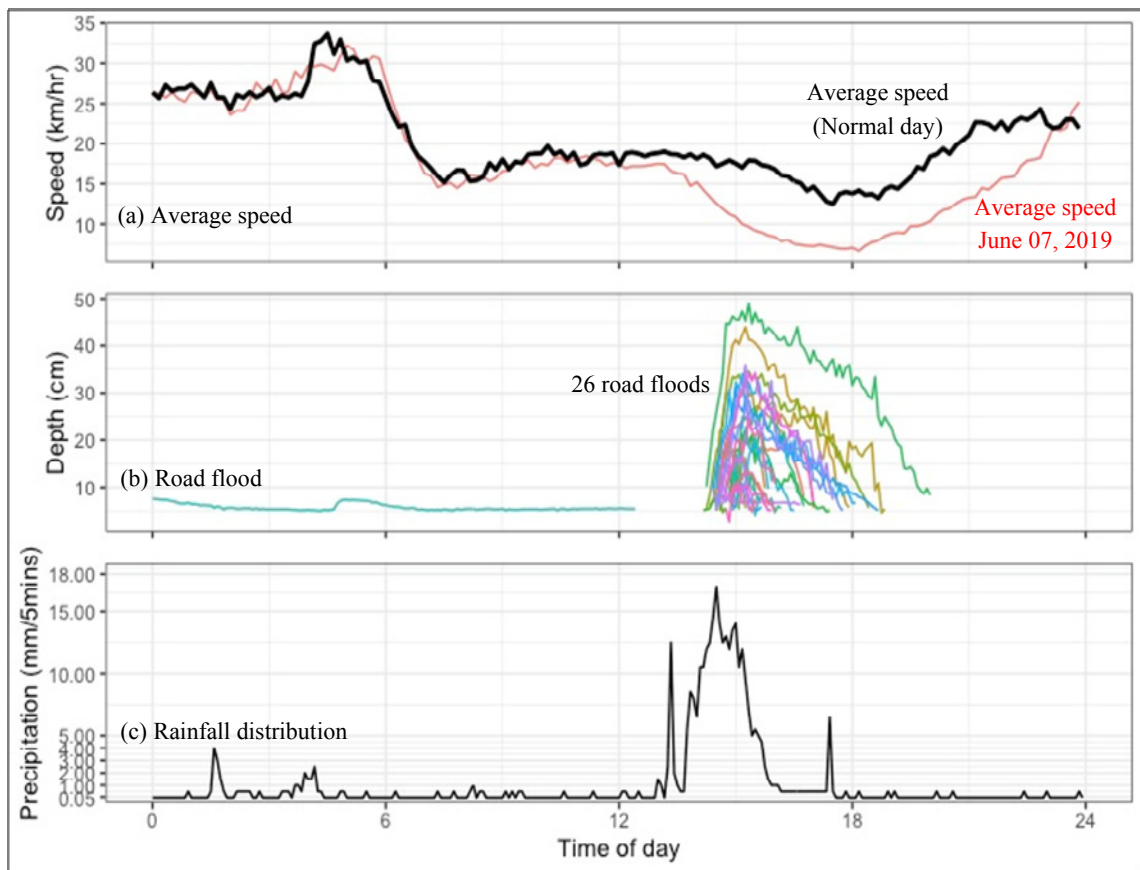


Fig. 1 Rainfall events on June 07, 2019.

the Sukhumvit area. This finding was consistent with Ref. [4]. They combined data from experiments and observations to create a depth-disruption function that related flood depth with vehicle speed. Using their model, an average depth of 30 cm reduced travel speed to 0 km/h as the ultimate threshold for safe driving of most vehicles.

From the above, understanding the impact of road floods on transportation performance has the potential to provide guidance for transportation management and urban planning in cities that are frequently affected by flooding. Traffic flow theory, as the study of interactions between travelers and infrastructure, can be used to rationally explain changes in traffic phenomena under different road network conditions. The concept of the Macroscopic Fundamental Diagram (MFD) was developed by Greenshields et al. [5] to establish a relationship between volume, speed, and density. MFDs are used to understand traffic flow

characteristics in complex urban networks [6, 7] and also to evaluate the performance of traffic control strategies.

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 [8, 9]. Traffic studies rely on fixed loop detector data. MFD estimation can be obtained in the area of the installed loop detector. However, the cost of installation and operation of the loop detector by the roadside is often high and, therefore, detectors can not be used everywhere. In developing countries, traffic detectors are concentrated in arterial roads and highways. With recent advances in GPS-enabled devices, mobile probe vehicles can now provide information on location, speed, and distance traveled

at regular intervals within a road network. Probe vehicles offer remarkable advantages compared with conventional static detectors.

This study estimated MFD parameters using probe vehicle trajectories during flood days. MFD parameters are useful to estimate the relationship between free-flow speed, maximum flow, and traffic jam density for road surfaces under any flood depths. Results can be used to build a road network model to determine travel routes by considering the effects of road degradation and then assessing travel delays and vehicle distribution in a given road flood.

2. Description of the Case Study Area

Bangkok has advanced economic growth and rapid urbanization compared to other members of the ASEAN community [10]. Urbanization patterns have been shown to have a significant effect on local precipitation from studies conducted in many urban areas [11-14].

In Bangkok, average total annual rainfall, as measured by the Thai Meteorological Department, is

in excess of 2,000 mm. Frequent road flooding also occurs in various areas even where rainfall does not cause major floods. Historical rainfall data collected from 131 meteorological stations installed around Bangkok are shown in Fig. 2a. Raster maps were generated to compare the amount of rainfall. Rainfall distribution was more spatially concentrated in the central business district (CBD), leading to increased risk of urban flooding.

Fig. 2b shows the 2019 statistical data of maximum road flood depths where detectors were installed to monitor flood conditions on roads and tunnels in Bangkok. The system operates at 5 minute intervals of data storage frequency and all data are stored for a lengthy time period in the MS SQL database as a very useful tool for road flood forecasting. A total of 71 sensors installed on important roads throughout urban Bangkok, with 8 sensors in tunnels measure and display real-time flood graphs. This research considered only two zones of Bangkok as the inner city and the urban fringe that are frequently flooded.

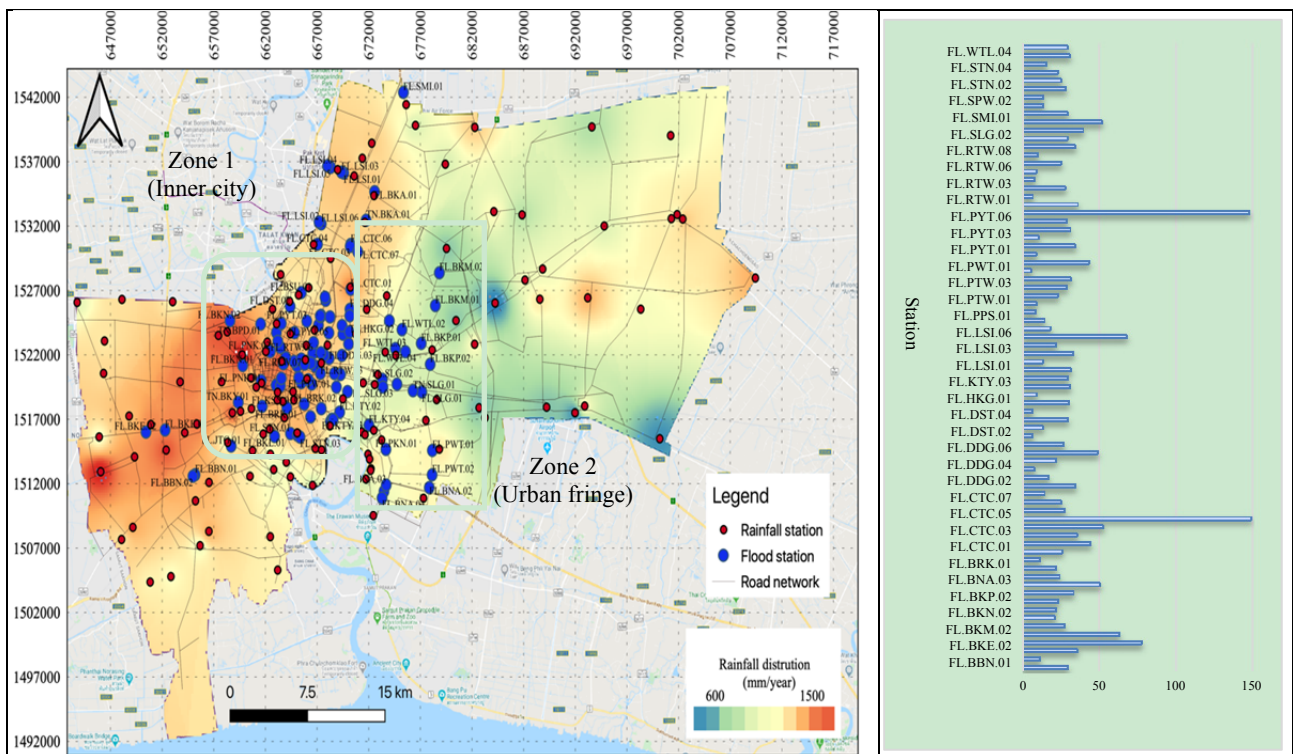


Fig. 2 The study area in the Bangkok metropolitan region.

As a first step, traffic-related data regarding the effects of flooding on the road network were collected from the Thai Intelligent Traffic Information Center Foundation as historical raw vehicles and mobile probe data from January to December 2019 [15].

Probe data for each day were saved as a CSV text file with structures of unique vehicle ID and GPS location collected every minute and also a time stamp, speed and vehicle heading direction. Data were collected within the center of Bangkok.

3. Methodology

Vehicle trajectory is the most intuitive measure of traffic conditions on urban arterials. First, we selected flood data corresponding to vehicle trajectory data (probe data) of similar date, hour, and minute intervals. Then, we calculated the probe vehicle penetration rate for the study area. Next, the average density-weighted network flows were estimated based on Edie's generalized definitions. Finally, we presented fundamental diagrams according to different water depths.

3.1 Vehicle Trajectory

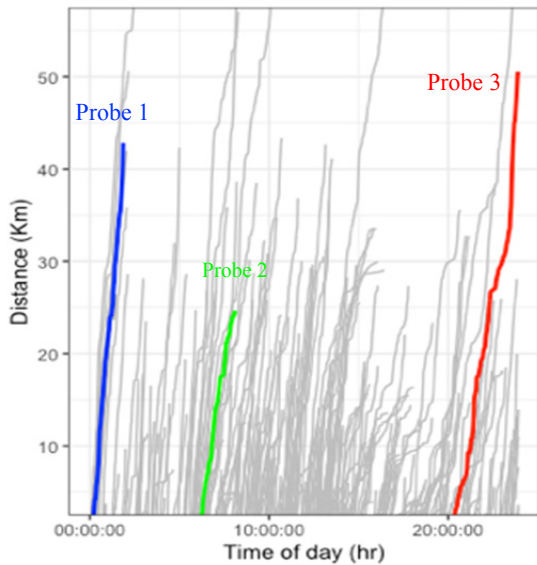
The location of probe vehicle trajectories is shown on a time-space diagram connecting all the points for

space at an incremental time of travel as Fig. 3a for a dataset extracted over a period of 24 hours.

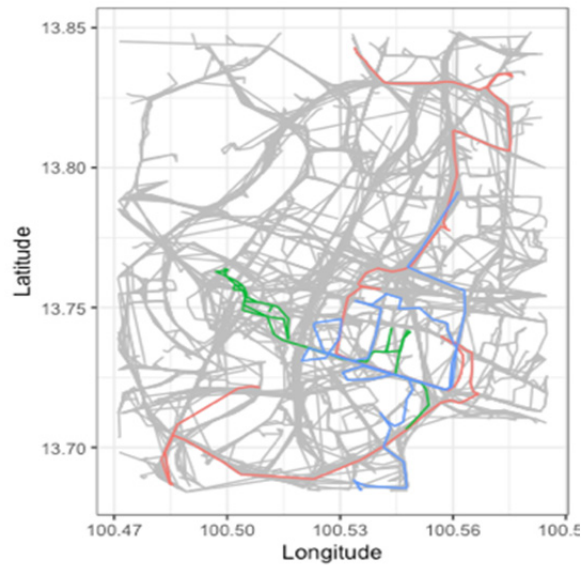
Fig. 3b shows routes passed by three different probe vehicles. Each probe vehicle had a different start/end time. To avoid a complicated plot, we only displayed three probe vehicle IDs, and each color represents a different probe vehicle track. To construct the MFD, we used the probe vehicle data for year 2019 during days when flooding occurred. The probe vehicles traveled an average of 60,000 km a day. The observed data are presented in order of starting positions on the network, along with a time stamp and an end position with a time stamp. Travel time between the start and the end of each observation was around 1 minute. For each observation, the 10 shortest trajectories between the start point and the endpoint were selected as the most probable.

The penetration rate of probe vehicles is a crucial factor for MFD estimation. If penetration rates vary regionally within a network, the estimated shape of the MFD can be distorted. To examine penetration rates, we calculated the penetration rate (ρ) every hour using the following equation:

$$\rho = \frac{N_{(d,i)}^p}{N_{(d,i)}} \quad (1)$$



(a) Time-space diagram



(b) Trajectories path

Fig. 3 Probe vehicle trajectories.

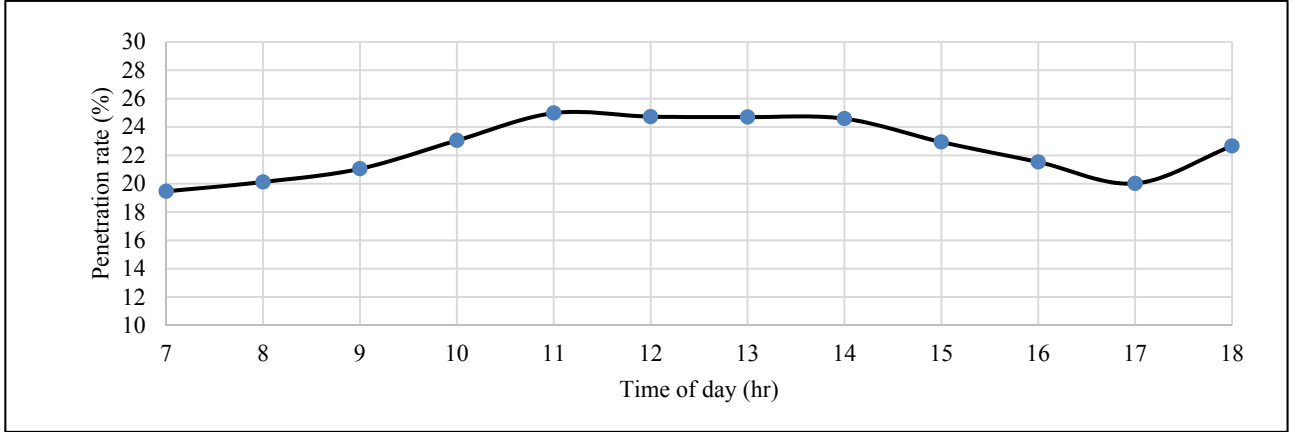


Fig. 4 Probe vehicles penetration rate.

where,

$N_{(d,i)}^p$ and $N_{(d,i)}$ are the number of probe vehicles traveling and number of actual vehicles in the network during time interval i on day d .

Estimated penetration rates (ρ) during the same time intervals on different days are shown in Fig. 4. We used an average penetration rate per day of 22.45% to estimate the MFDs. This was consistent with Nagle & Gayah [16] who suggested that estimates were accurate and reliable when the penetration rate reached 20%.

3.2 MFD Estimate Using Probe Vehicles

The average network flow $\bar{q}(d,i)$, density $\bar{k}(d,i)$, and speed $\bar{s}(d,i)$ during time interval i on day d , were calculated from the trajectory data of all vehicles using Edie's generalized definitions [17] as follows:

$$\bar{q}(d,i) = \frac{\sum N_{(i,d)}^p \cdot \bar{d}_{p(d,i)}}{\rho LT} \quad (2)$$

$$\bar{k}(d,i) = \frac{\sum N_{(i,d)}^p \cdot \bar{t}_{p(d,i)}}{\rho LT} \quad (3)$$

$$\bar{s}(d,i) = \frac{\bar{d}_{p(d,i)}}{\bar{t}_{p(d,i)}} \quad (4)$$

where,

$\bar{d}_{p(d,i)}$ and $\bar{t}_{p(d,i)}$ are average distance traveled (vehicle kilometers traveled, VKT) and average time spent (vehicle hour, VHT) by probe vehicles, L is the total length of all networks, and T is the identical length of the time intervals during day d .

4. Results and Discussion

Figs. 5 and 6 show the relationship between average flow, average speed, and average density of urban road networks in zones 1 and 2 in Bangkok at 10 minute intervals. Variations in the shape and form of the MFD were examined when road flooding increased from 0, 5, 10, 15, 30, and more than 30 cm, respectively.

Flood depth effects on maximum flow reduction showed different ranges of fluctuation between zones. Maximum flow reduction on inner-city (zone 1) roads increased with flood depth (Fig. 5). Maximum flow greatly reduced from 700 vehicles/hour under dry conditions to 500 vehicles/hour under flooding. At flood depths of 0-30 cm, reductions in maximum flow showed a similar tendency. Flood depth increase to over 30 cm caused high dispersion and the road was completely closed [4]. Free flow speed (Fig. 6) was 40 km/h under dry conditions. This greatly reduced to 25 km/h under flooding, with a slight increase in traffic jam density. For the urban fringe (zone 2), reductions in maximum flow under different flooding depths indicated a similar tendency. Without road floods, maximum flow was 780 vehicles/hour and this declined to 750 vehicles/hour under flooding conditions.

Overall, the MFDs of flood day are more scatters and deviation than the flood day. In other words, the flooding changes the MFDs shape, which indicates the traffic state of the given network, especially in the inner city.

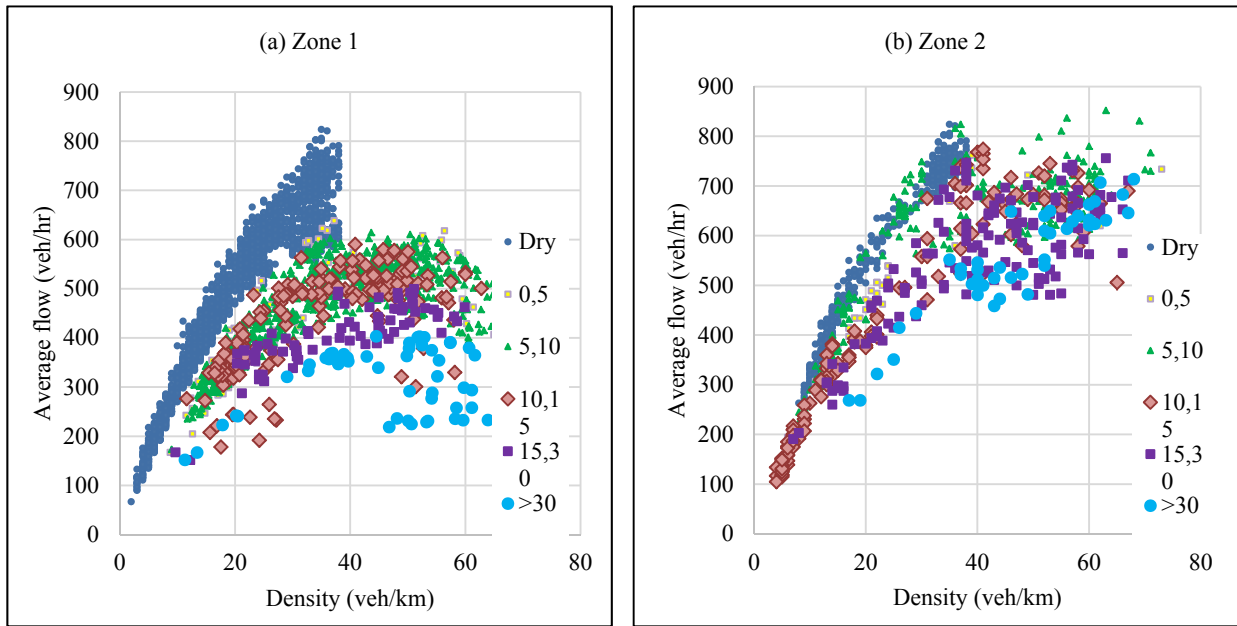


Fig. 5 Average density-average flow relationship.

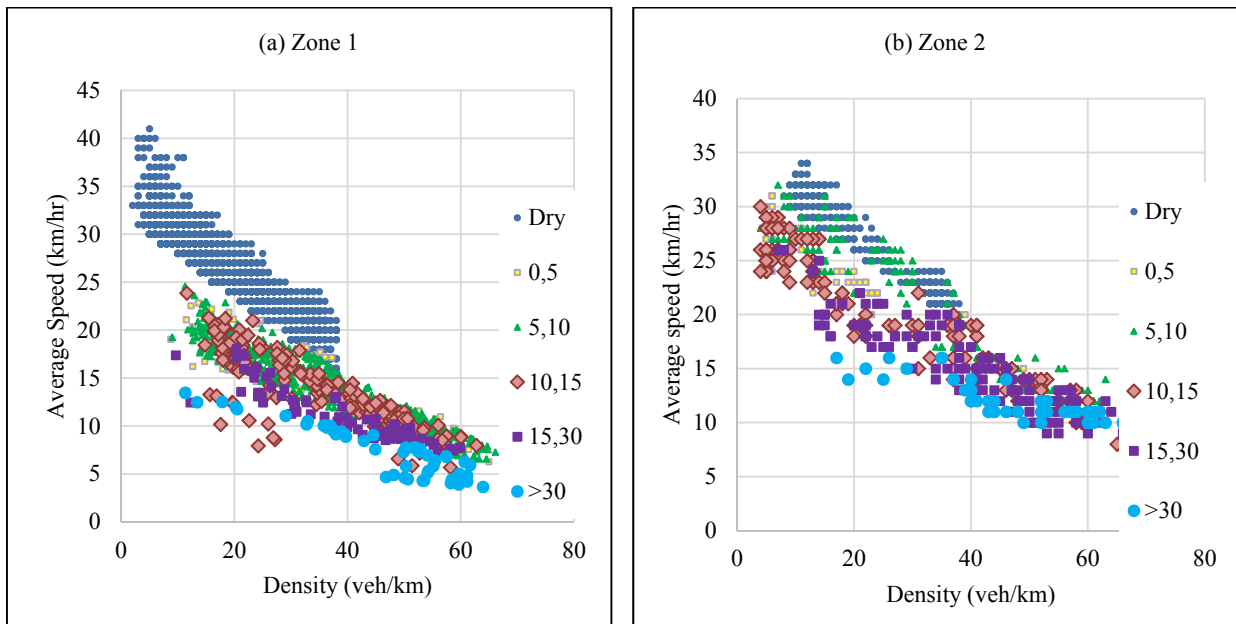


Fig. 6 Average density-average speed relationship.

The MFD curves are shown in Figs. 7 and 8 under different flooding depths. Negative effects increased with increase in flood depth. The R-square value of fitting MFD curves under each flooding depth and the state turning point are also given. R-square is the statistic of the goodness of fit and can be used to describe discrete changes in the MFD. We found that the R-square value reduced as flood depth increased,

while continuity also decreased.

Relationships under both dry and different flood depths were obtained by analyzing and fitting the parameters of the Greenshields regression equations [18] 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 1.

Table 1 Impact of flooding on traffic-related parameters.

Depth (cm)	Zone 1				Zone 2			
	R _{square}	q _c	k _j	u _f	R _{square}	q _c	k _j	u _f
Dry	0.951	696	80	35	0.981	768	85	36
0-5	0.875	567	89	26	0.972	736	85	33
5-10	0.855	541	93	23	0.958	722	98	32
10-20	0.749	514	93	21	0.878	684	98	29
20-30	0.691	451	106	19	0.863	668	110	26
> 30	0.363	349	85	14	0.710	735	198	16

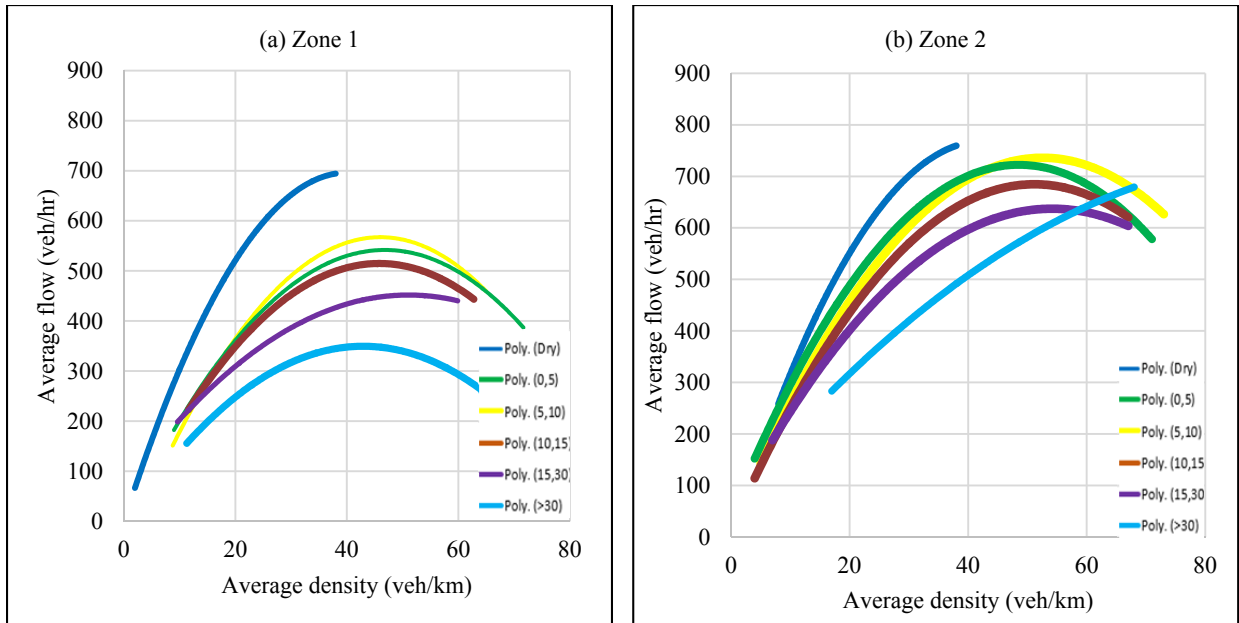


Fig. 7 Fitting MFD curves of average density-average flow.

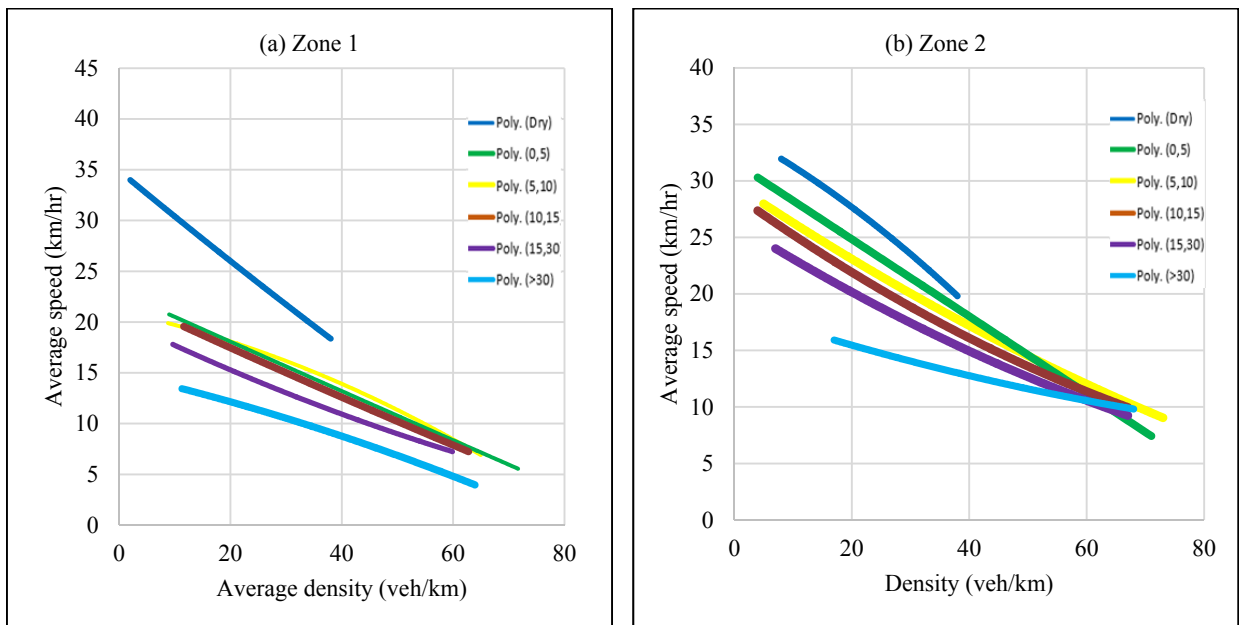


Fig. 8 Fitting MFD curves of average density-average speed.

5. Conclusions

Results were presented as Macroscopic Fundamental Diagrams (MFDs) using real data sets of the signalized arterial network in urban Bangkok. MFD shapes were calculated for road networks of two zones using traffic data sourced from probe trajectories. MFD throughout the year 2019 was divided into two conditions as dry and flood (0-5, 5-10, 10-15, 5-30, and > 30 cm). The shape of the MFD for the two zones was different. The MFD slope (Fig. 5) of zone 1 quickly decreased under flood conditions compared to dry conditions. The shape under flood conditions from 0-30 cm showed slight differences. When flood depth increased to over 30 cm, the MFD shape became unusually distributed. Speed distribution in flood conditions (Fig. 6) greatly reduced compared to dry conditions. In zone 2, traffic was not as crowded compared to zone 1. MFD shapes (Fig. 5) under flood conditions showed a slightly decreased slope compared with dry conditions until flood depth exceeded 30 cm, similar to zone 1. The MFD deformation data indicated shape changes resulting from two factors as (1) road network capacity or supply was degraded under a flood event, and (2) traffic volume or demand was different in each zone. These findings provide insights into the impacts of flooding on urban road traffic. Results can be used for modeling these impacts to assess road users' route choice behavior. Evaluation of flood depth as a traffic model can be used to estimate the time required to evacuate people from risk areas or improve traffic light control using basic data according to the MFD shape of each area.

Acknowledgement

(1) Historical raw vehicles and mobile probes data in Thailand from The Intelligent Traffic Information Center Foundation.

(2) Road flood from Department of Drainage and Sewerage, Bangkok.

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