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Impact of Rainfall Condition on Traffic Flow and Speed: A Case Study in Johor and Terengganu

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Graphical abstract

Table 1 Case 1: Traffic flow and speed at Lane 1, Kuala Abang, Terengganu

Prevailing Condition	Average Volume (veh/h)	Capacity (pce/hr)	Mean Speed (km/h)	Free Flow Speed (km/h)	Speed at Capacity (km/h)
Dry	420	1600	72.1	75.7	48.2
Light rain	432	1088	69.6	75.1	44.6
Moderate rain	474	1468	67.7	75.0	41.4
Heavy rain	427	1450	66.7	73.9	44.1

Abstract

This paper explores the impact of various rainfall conditions on traffic flow and speed at selected location in Terengganu and Johor using data collected on two-lane highway. The study aims to quantify the effect of rainfall on average volume, capacity, mean speed, free-flow speed and speed at capacity. This study is important to come out with recommendation for managing traffic under rainfall condition. Traffic data were generated using automatic traffic counters for about three months during the monsoon season. Rainfall data were obtained from nearest surface rain gauge station. Detailed vehicular information logged by the counters were retrieved and processed into dry and various rainfall conditions. Only daylight traffic data have been used in this paper. The effect of rain on traffic flow and speed for each condition were then analysed separately and compared. The results indicated that average volumes shows no pronounce effect under rainfall condition compared to those under dry condition. Other parameters, however, show a decrease under rainfall condition. Capacity dropped by 2-32%, mean speed, free-flow speed and speed at capacity reduced by 3-14%, 1-14% and 3-17%, respectively. The paper recommends that findings from the study can be incorporated with variable message sign, local radio and television, and variable speed limit sign which should help traffic management to provide safer and more proactive driving experiences to the road user. The paper concluded that rainfall irrespective of their intensities have impact on traffic flow and speed except average volume.

Keywords: Traffic flow; speed; capacity; volume; free-flow speed; speed at capacity; rainfall

1.0 INTRODUCTION

Weather is one environmental factor that is known to affect the performance of the surface transportation system and road safety. Also, it is often considered as an external factor that can affect traffic operations [1]. The influence of weather conditions on road network operation due to the various driver behaviours has been recognised since the 1950s [2]. Inclement weather makes a driver's task more difficult and can lead to accidents. According to Maze *et al.* [3], inclement weather (fog, rain, snow, high winds, and extreme cold) impacts traffic operations and safety performance during a significant proportion of the year. There are three predominate traffic variables that weather impacts: (i) traffic demand-in the face of inclement weather some trips will be postponed, deferred, or eliminated; (ii) traffic safety-crash rates (crashes per km) increase dramatically during inclement weather; and (iii) traffic flow relationships change-changes in the relationship between volume, speed, and density result in reduced capacities [3].

Out of the weather events, rainfall has the most significant impact on the traffic flow due to its spatiotemporal nature. Therefore it's not unusual for driver to become agitated before, at the onset, during and even after any rainfall. It's a global phenomenon. The principal problems of rainfall for road traffic are: (i) poor visibility conditions (ii) decreased adhesion coefficient between the road surface and vehicle and (iii) increased aquaplaning. Those problems would exacerbate traffic stream operation. The impact of these disturbances to the traffic stream is such that the sight distances of the highway are reduced, speed of vehicles are decreased, headway are increased relative travel time is lost and the risk of crash increases. Therefore, practitioners still need tools to aid in deploying operational strategies and traffic management techniques in response to inclement weather.

Rainfall is a very important weather element in Malaysia. The mean annual rainfall in Malaysia is considered significantly high at 2500 mm, and the variation by places is in the range of 1500 mm to over 4000 mm annually [4]. It is influenced by the Southwest monsoon and the Northeast monsoon. However, the Northeast monsoon brings in more rainfall compared to the Southwest monsoon. Notwithstanding the amount of rainfall on Malaysian roadways, studies into their influence on traffic flow have been very limited at all. Thus, the aim of this study is to quantify the effect of rainfall on traffic flow and speed, which focuses on average volume, capacity, mean speed, free-flow speed and speed at capacity. This study is important to come out with recommendation for managing traffic under rainfall condition. Therefore, an overview of the literature on the impact of rainfall conditions on traffic flow and speed is presented in the next section. The third section describes the data and method that are used and presents a short description of the study area. In the fourth section, traffic flows and speeds are compared during rainfall and dry conditions. The fifth section describes possible strategies to manage traffic under rainfall condition and the sixth section summarizes the study.

■2.0 IMPACT OF RAINFALL ON TRAFFIC FLOW AND SPEED

Rainfall event can significantly affect travel demand, driving behaviour, traffic flow characteristics and safety [5-11]. Eventhough rainfall is beyond the extreme weather conditions (tornados, floods, typhoons, hurricanes etc.), but it offer a less compressed time frame to the decision makers, and allow drivers to retain an acceptable amount of control. Still this control may be compromised by physical factors such as visibility, physical discomfort (cold) and reduced pavement friction in the presence of precipitation condition [12]. Thus, rainfall affects driver behavior since they are tried to accommodate to the new situation by changing their driving style.

According to Rao and Rao [13], capacity is one of the most important elements of road space supply. When capacity is compromised, motorists will experience increase in travel time. They overtake less, drive slower and increase their following distance. In Highway Capacity Manual (HCM), capacity of a facility is defined as 'the maximum hourly rate at which persons or vehicles can reasonably be expected to traverse a point or uniform section of a lane or roadway during a given time period under prevailing roadway, traffic and control conditions [14]. From the definitions, it is clear that the important concepts of capacity rely on prevailing conditions. Any change in the prevailing conditions would result in a change in the road capacity. Although the conventional guidelines for the assessment of traffic flow quality around the world, including the HCM [14] has traditionally treated capacity of highway facilities as a constant value [15, 16], but it must be understood that there is no generally valid single capacity value. Even under ideal conditions, a constant value of capacity is not attainable in practice [15, 17-19]. Other studies also showed that capacities vary under non-ideal conditions as well [20, 21]. Capacity is a stochastic nature because of variations in individual driver behaviour, vehicle characteristic and changing road and weather conditions [17].

Several studies have examined the impact of rainfall condition specifically on traffic speed and flow. Tanner [5] investigated the effect of weather on traffic flow in England and he found that traffic flow and intensity of precipitation has negative correlation. According to the HCM [14], light rain does not have a notable effect on speed until water accumulates on the pavement. Lamm *et al.* [22] reported that speeds were not influenced by the presence of wet pavement until visibility was affected. Accordingly, light rain did not appear to have noticeable impacts on traffic flow compared to heavy rain that resulted in 10% to 15% reduction in capacity. Similarly, a study by Zhang *et al.* [30] found that visibility and pavement friction on roadways are certainly reduced under heavy raining conditions and thus cause a reduction in traffic speed and road capacity.

Other researchers have found that both light and heavy rain have cause reduction in speed and capacity. Smith *et al.* [10] conducted a study in Virginia on the impact of different rainfall intensity levels on freeway capacity and operating speeds. Their results indicated that both light (0.25–6.35 mm/hour) and heavy rains (more than 6.35 mm/hour) decreased operating speeds by 5-6.5%. In order to determine the change in capacity, the mean of the highest 5% flow rates was used by Smith *et al.* [10]. It was found that light rain decreased capacity by 4-10% while heavy rain led to a capacity decrease in the range of 25-30%. The rainfall impact speed and capacity was also studied by Argawal *et al.* [24]. The analysis showed that very light rain (less than 0.25 mm/hour), light rain (0.25–6.35 mm/hour) and heavy rain (more than 6.35 mm/hour) reduced operating speed from 1-2%, 2-4% and 4-7%, respectively. They also reported that very light rain and light rain decreased capacity by 1-3% and 5-10%, respectively.

A study sponsored by Federal Highway Administration [25] in three major metropolitan areas in the U.S. confirmed a decrease in speed and capacity during rainfall. In light rain, 2-4% and 10-11% reduction were found in measureable free flow speed and capacity, respectively. Chung *et al.* [9] reported that the free flow speed decreased from 4.5% during light rain to 8.2% during heavy rain in Tokyo, Japan. For light rain, the HCM [14] reports observed decreases of free flow speed about 1.6 km/h. For heavy rain, the observed free flow speed decrease was 3.2–4.8 km/h. Pham *et al.* [26] also recognised that the median free flow speed at 500-600 veh/h fell by 0.91 percent, from 87.9 km/h in fine weather condition to 87.1 km/h in rain condition.

Even though most researchers report reductions in traffic flow and speed during rainfall, but the estimated speed reductions vary widely. This divergence could be attributable to difference of rainfall category used, reliance on faulty speed-flow relationship, questionable quantitative estimation methods or static passenger car equivalent values.

■3.0 DATA AND METHODOLOGY

In peninsular Malaysia, the rainy season is in the period of November through January in the east, October through November and April through May in the west, with June and July as the driest period. Consequently, the main studies were carried out at two sites located at Kuala Abang, Terengganu and Pengkalan Raja, Johor between November 2009 and January 2010. Typical setup of impact study sites is shown below in Figure 1.

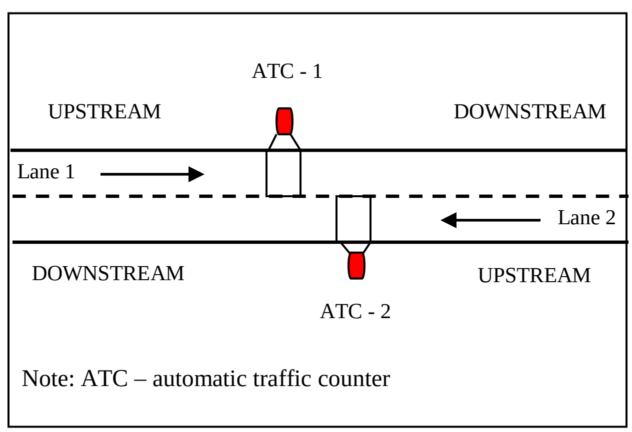

Figure 1 Layout of typical survey site

All sites were on two-lane federal highway and chosen to represent eastern (Terengganu) and western (Johor). It is pertinent that rain gauges be located near the highway section under study, therefore study sites are located at less than 2 km from the nearest rain gauge. On-site volume, speed, headway and vehicle type data were captured continuously for three months. Two pneumatic tubes were set at 1 m apart across the carriageway lane width and connected to an automatic recorder (ATC). Three classes of rainfall intensity (light for precipitation less than 2.5 mm/h, moderate for precipitation between 2.5 mm/h and less than 10 mm/h and heavy for precipitation more than 10 mm/h and less than 50 mm/h) were used in the study. Five classes of vehicles were identified according to Malaysian Highway Capacity Manual [27]. Based on the data, average volume and mean speed were estimated under prevailing weather condition. Daylight off-peak data were used in order to remove the effect of peak conditions on speed.

Since, it is impossible to obtain capacity directly from observed data, the capacity as well as speed at capacity and free-flow speed were estimated based on the volume, speed and density method otherwise called the fundamental diagram method [28,29]. The procedure used in this study is summarized as follows:

i. select traffic data during off-peak period under dry and daylight conditions;
ii. aggregate traffic data into 5 minutes interval;
iii. determine appropriate PCE values for this condition;
iv. estimate flows by way of a multiplier (x12) after considering appropriate pce values;
v. determine harmonic mean of speeds with variances and standard deviations;
vi. derive densities from flows and speeds;
vii. derive flow-density equations with negative intercept and passing through the origin;
viii. test model equations for validity;
ix. use model equation with negative intercept to estimate critical densities by differentiating flow with respect to density;
x. determine road capacities by plugging critical densities into model equations;
xi. determine speed at capacities; and
xii. use model equation passing through the origin to estimate free-flow speed.

4.0 EMPIRICAL FINDINGS AND DISCUSSION

The effect of rainfall on traffic flow and speed is summarised in Tables 1 to 4. The average volumes for daylight off-peak hours for all cases shows no pronounce effect under rainfall condition compared to those under dry condition, even though the mean speed has a decrease. However, capacity decreases with increases in rainfall intensity. The results showed that presence of rain reduced capacity by 2-32%. In overall, the drop in capacity has not shown any pertinent trend except that the drop occurred probably at the onset of rainfall (cases 1 and 2) while drivers are adjusting to the change in weather condition.

Also, speed decreases as the rain intensity increases. For mean speed, the range of reduction is 3-14% in all cases suggesting that drivers were constrained by rainfall condition. Interestingly, free-flow speed dropped by 1-14% because of rainfall, thus suggesting that at reduced traffic flow, even if it is one vehicle on the roadway, maximum free-flow speed cannot be reached. It depicted a free-flow situation where drivers cannot choose speeds due to poor weather condition. For speed at capacity, the drop is in the range of 3-17%. However, for the case 1, the speed at capacity for heavy rain condition was significantly higher than moderate rain condition but still less than light rain condition. This situation not occurs at other cases. It might be because drivers were able to adjust to prevailing condition or the traffic stream had high percentage of drivers with knowledge of the local area.

Table 1 Case 1: Traffic flow and speed at Lane 1, Kuala Abang, Terengganu

Prevailing Condition	Average Volume (veh/h)	Capacity (pce/hr)	Mean Speed (km/h)	Free Flow Speed (km/h)	Speed at Capacity (km/h)
Dry	420	1600	72.1	75.7	48.2
Light rain	432	1088	69.6	75.1	44.6
Moderate rain	474	1468	67.7	75.0	41.4
Heavy rain	427	1450	66.7	73.9	44.1

Table 2 Case 2: Traffic flow and speed at Lane 2, Kuala Abang, Terengganu

Prevailing Condition	Average Volume (veh/h)	Capacity (pce/hr)	Mean Speed (km/h)	Free Flow Speed (km/h)	Speed at Capacity (km/h)
Dry	422	1595	70.8	75.1	44.9
Light rain	408	1531	68.6	73.3	43.7
Moderate rain	445	1538	67.4	72.4	42.9
Heavy rain	455	1162	66.7	69.0	39.1

Table 3 Case 3: Traffic flow and speed at Lane 1, Pengkalan Raja, Johor

Prevailing Condition	Average Volume (veh/h)	Capacity (pce/hr)	Mean Speed (km/h)	Free Flow Speed (km/h)	Speed at Capacity (km/h)
Dry	629	1372	63.2	70.0	43.9
Light rain	630	1345	59.2	69.8	41.1
Moderate rain	625	1342	58.8	63.2	40.8
Heavy rain	656	1233	54.3	59.9	36.6

Table 4 Case 4: Traffic flow and speed at Lane 2, Pengkalan Raja, Johor

Prevailing Condition	Average Volume (veh/h)	Capacity (pce/hr)	Mean Speed (km/h)	Free Flow Speed (km/h)	Speed at Capacity (km/h)
Dry	650	1324	63.2	70.1	45.2
Light rain	670	1235	60.3	68.0	40.6
Moderate rain	638	1214	58.5	66.7	40.5
Heavy rain	672	1201	57.6	64.1	40.3

■5.0 STRATEGIES TO MANAGE TRAFFIC UNDER RAINFALL CONDITION

The study shows traffic flow and speed on selected highway in Peninsular Malaysia changes due to rainfall irrespective of their intensities because drivers respond to the rainfall conditions by lowering their operation speeds. The involuntary lowering of operating speed is often caused by poor visibility and reduced road surface traction. Therefore, there is a need to take steps to improve traffic flow and operation during rainfall condition, with the aim of minimizing delays and crashes. The method that can be applied is dissemination of road weather information, advisory and warning to the public through tools such as variable message signs, local radio and television. Thus, it will helps the public to estimate impacts of rainfall, make better travel plans, select more appropriate routes, and avoid unnecessary travel. Consequently, traffic safety can be improved by better traveler information. Information dissemination is divided into two categories: information provision to drivers on the road is to improve traffic safety under adverse weather conditions; information provision to the public is to affect their travel mode selection and plan, and adjust traffic demand [23]. Other method is to deploy variable speed limit signs when weather condition deteriorates to the point that hazardous conditions are impending. The speed limit decrease is intended to alert drivers of conditions downstream, thus helps minimize the likelihood of collisions.

■6.0 CONCLUSION

Based on comparisons between traffic flow and speed data under various rainfall intensities and dry condition, the paper recorded the reductions of capacity and speed on the highway except average volume. The results indicate that the capacity on the selected highways under rainfall condition have a 2-32% decrease when compared to those under dry condition. The speed generally reduces under rainfall condition with mean speed, free-flow speed and speed at capacity have drop about 3-14%, 1-14% and 3-17%, respectively. The paper concluded that rainfall irrespective of their intensities have impact on traffic flow and speed except average volume.

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