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EFFECT OF RAINFALL ON TRAFFIC FLOW CHARACTERISTICS DURING NIGHT TIME

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Graphical abstract

Abstract

Understanding traffic behavior for obtaining a smooth, safe and economical traffic operation requires a thorough knowledge of traffic flow parameters and their mutual relationships.Eventhough adverse weather can reduce traffic efficiencies, there are still questions to answer regarding the relationship between weather conditions and traffic flow at night. This paper presents an investigation of the rainfall effects to the traffic flow characteristics on atwo-lane rural highway during night time. The traffic data and corresponding rainfall data for uninterrupted road segment of Federal route 3 at Dungun, Terengganu were collected under road lighting condition during the north-east monsoon season. The effect of good weather condition, light rain, moderate rain and heavy rain conditions on speed, flow and density were quantified and compared. Results from the analysis indicate that mean speed, mean flow and mean density are reduced under various rainfall conditions. In general, the impact of good weather and various rainfall conditions on Greenshield's fundamental traffic flow relationship have weak correlations except for the relationship between flow and density. The important points in the fundamental diagram derived from flow-density relationships indicated that critical density, maximum flow, critical speed, jam density and free flow speed of roadway all decrease as rainfall intensity increases. It can be concluded that traffic flow characteristics of two-lane rural highway in Terengganu are affected by rainfall conditions.

Keywords: Rainfall, weather impact, speed-flow-density relationship, traffic flow characteristics

1.0 INTRODUCTION

Knowledge of fundamental traffic flow parameters and their mutual relationships are crucial aspects in understanding and analyzing the behavior of traffic as well as in planning and designing the facilities for a smooth, safe and economical traffic operation. Using the main fundamental parameters which consist of flow, speed and density, numerous mathematical analyses and models have been extensively developed since the 1930s [1-5]. The relationships among these parameters can be affected by various factors, such as driver characteristics, vehicle type compositions, weather and road surface conditions [6-8].

Among others, the effect of weather conditions on driver behavior and the manner in which a transportation system needs to be operated has been recognized since the early 1950's [9]. The different classification schemes for weather conditions have

been used by transport researchers because these conditions differ considerably in type and in magnitude [10]. Some weather conditions are extreme in nature such as tornados, floods, typhoons and hurricanes and thus may trigger a different response by the drivers. Other inclement weather conditions such as rainfall, snow and fog offer a less compressed time frame to the decision makers, and allow drivers to retain an acceptable amount of control on their vehicles; this control may be less than under "normal everyday" situation due to physical factors such as visibility, physical discomfort (cold or hot temperatures) and reduced pavement friction with the tires when precipitation or icy conditions prevail. The change in the driver's behavior may result in, among others, deterioration of the network's travel times and speeds, which also causes changes in the behavior of the vehicle collectives such as the traffic density and the traffic volume.

The presence of adverse weather such as fog, dust, rain, snow, or smoke in the atmosphere can makes a driver's task more difficult [11]. This is because in such weather, visibility of the driver will become poorer, adhesion coefficient between the road surface and vehicles decrease and these conditions cause the driver to reduce his or her speed. In order to comprehend the behaviour, most studies have explored the relationship between weather conditions and traffic flow [12-19]. Although many researchers concluded that adverse weather could reduce traffic efficiencies based on key traffic parameters, there are still questions about the relationship between weather conditions and traffic flow under road lighting condition since there has been limited focus in the literature investigating this issue.

Therefore, thisstudy aimed at investigating empirically the influence of rainfall on traffic flow characteristics of rural two-lane highway under road

lighting condition at night. In the light of discussion so far, the remainder of the paper has been divided into four sections. In the following section, the concepts on fundamental relations of traffic flow will be discussed in section 2.0, followed by methodology in section 3.0. While, results and analysis are presented and discussed in section 4.0. Conclusions are drawn in the final section.

2.0 FUNDAMENTAL RELATIONS OF TRAFFIC FLOW

Traffic flow theory is required to rationally explain the traffic phenomena that are observed on the road section. It enables more accurate prediction of behaviour in a new traffic situation. It is concerned with the movement of discrete objects in real time network in two dimensions. As shown in Figure 1, a diagram shows the relation between two of the three variables in which the variables are speed, flowand density.The third variable can always be recovered by means of the relationship as follow:

$$q = u \times k \tag{1}$$

Where$q$ is flow (veh/h), u is speed (km/h) and k is density (veh/km). The third variable in the q-u and the q-k diagram is an angle. The flow rate in the u-k diagram is represented by an area. The most important points in the fundamental diagram are the roadway capacity (q_c), the critical density (k_c), the critical speed (u_c) jam density (k_j) and the free flow speed (u_f). The diagram has four boundaries conditions: (i) $q = 0$ at $k = 0$; (ii) $q = 0$ at $k = k_j$; (iii) $u = 0$ at $k = k_j$; and (iv) $u = u_f$ at $k = 0$. Free flowing condition occurs when the value of k is less than k_c, while the congested condition occurs when k is more than k_c.
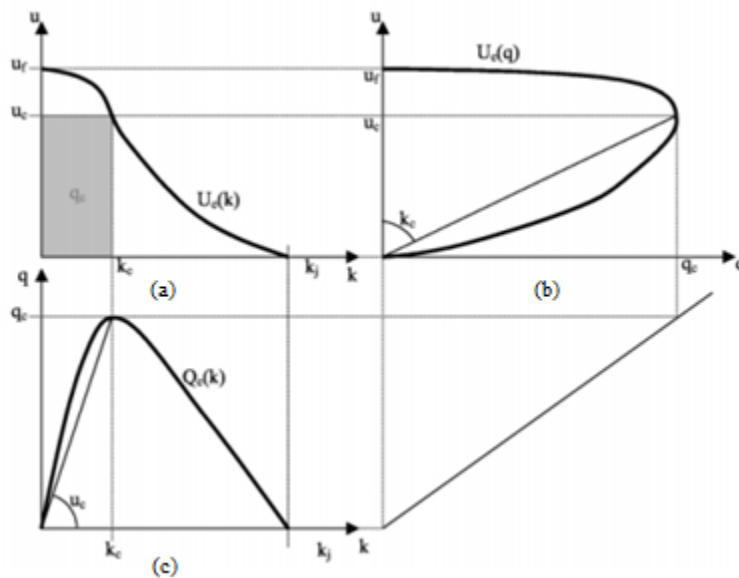

Figure 1 The three related fundamental diagrams: (a) u-k, (b) q-u and (c) q-k relationships[20]

The fundamental diagrams of flow and density, density and speed, speed and flow are important to thoroughly understand theoretically the effects of rainfall on rural two-lane highway characteristics of traffic flow. As shown in Figure 2, it is believed that rainfall will affect fundamental traffic flow diagram by shrinking the curve, diminishing capacity (from q_{c0} to q_{c1}), reducing free-flow speed (from u_0 to u_1),

and increasing density (from k_0 to k_1) with the same traffic demand under uncongested traffic condition [17,21]. Therefore, this study will investigate the effect of rainfall on traffic flow characteristics by focusing on speed-flow-density relationships and the important points such as critical density, maximum flow, critical speed, jam density and free flow speed.
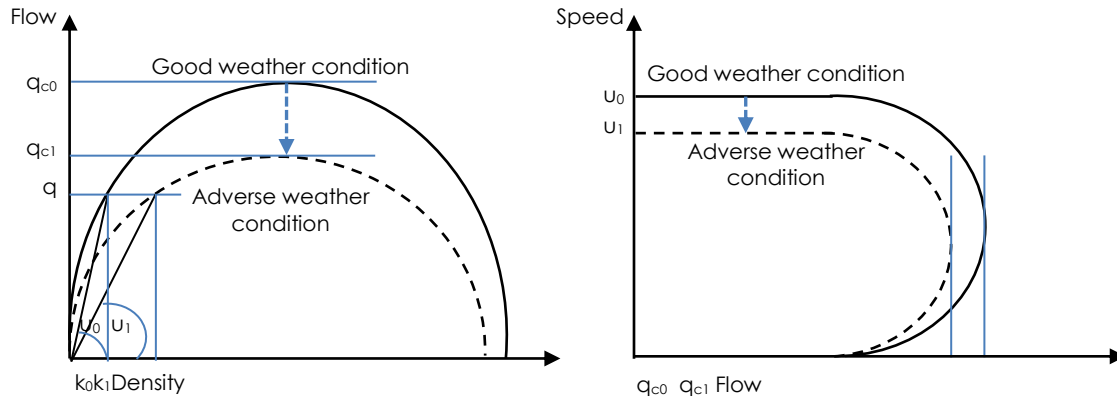

Figure 2 Changes of fundamental diagram due to adverse weather [17,21]

3.0 METHODOLOGY

A segment of two-lane highway at Dungun, Terengganu was chosen as the study site as shown in Figure 3. It is a part of Federal Route number 3 that connects Rantau Panjang in Kelantan until Johor Bahru in Johor.The selected segment is a single 10.6 m carriageway with 1.8 m shoulder width. The road is classified as a paved federal roadway built under the JKR R5 road standard with design speed of 100 km/h. The road, which is under jurisdiction of Public Work Department Malaysia has 15000 to 20000 annual daily traffic volume. The design life for pavement is 20 years, allowing maximum speed limit up to 90 km/h although a posted legal speed limit of 70 km/h is in operation. It has a level terrain, road light, straight road section, good asphaltic concrete road surface, uninterrupted traffic flow and not influenced by side parking. Existing side drain at this site can eliminate the effect of surface runoff on traffic performance during the rainy season.

Traffic data obtained in this study was collected from November 2010 until February 2011 using automatic traffic counter installed at selected uninterrupted road segment as illustrated in Figure 4 during the north-east monsoon season. While, the rainfall data was obtained from Department of Irrigation and Drainage's rain gauge station supplemented by local survey data. Traffic data between 8:00 PM and 12:00 AM was organized to correspond with rain intensities in order to obtain traffic data under good weather and rainfall conditions. The categories of rain intensity were identified in

accordance World Meteorological Organization standard as follows: good weather (i = 0 mm/h); light rain (i < 2.5 mm/h); moderate rain (2.5 ≤ i < 10.0 mm/h); heavy rain (10.0 ≤ i < 50.0 mm/h) and very heavy rain (i ≥ 50.0 mm/h).

Figure 3 Selected study site

The traffic data under good weather and each rain intensity classification were analyzed separately into 5 minutes interval. Five classes of vehicles were distinguished: class 1 - cars/small vans/utilities, class 2 – lorries (with 2 axles)/ large vans, class 3 - large lorry, trailers, heavy vehicles with 3 axles and more, class 4 – buses, and class 5 – motorcycles. However, motorcycles were excluded from analysis since most of these motorcyclists used the road shoulder at the

selected road segment. The aggregated database contains the rate of flow, average speed (harmonic mean) and density (derived from rate of flow and average speed) used for analysis.


(a)

(b)
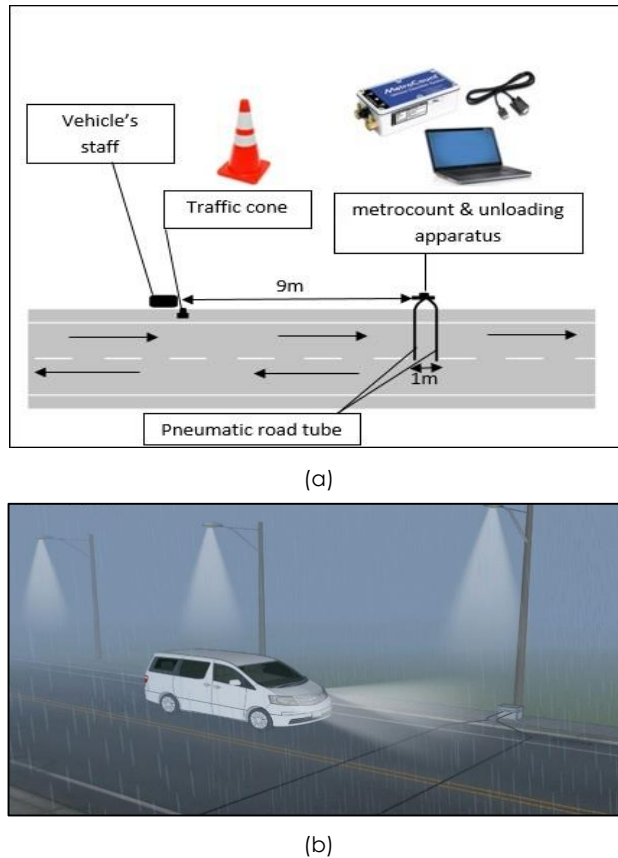
Figure 4 Typical layout of the study site: (a) equipment arrangement during installation of automatic traffic counter and the process of downloading data (b) traffic data collection process

4.0 RESULTS AND DISCUSSION

In order to obtain some background information about the traffic conditions of the study site and the potential differences between them, speed-flow-density relationships for good weather and various rainfall conditions are plotted in Figure 5. As can be seen from this figure, all of the points are scattered under uncongested section, which clearly shows that the traffic operations is under free-flow condition.

Table 1 shows the descriptive statistics for speed-flow-density data under good weather and rainfall conditions. In general, mean speed, mean flow and mean density decreased gradually with the increase of rainfall intensity. By comparing with good weather condition, the range of reduction for mean speed is between 3.1% during light rain and 6.9% during heavy rain. The pattern of this finding was found consistent with the conclusion drawn by Smith *et al.* [22] which state that there is a significant reduction in operating speed when rain of any intensity as compared to

good weather. A similar pattern was also observed for mean density and mean flow, where the reductions are up to 38.9% and 44.9%, respectively. These changes evidently show the impact of rainfall on traffic operations due to change of roadway environment, driver behaviour and traffic flow. As a consequence, drivers will usually choose lower speeds and longer headways in order to reduce the risk of accident.

(a)

(b)

(c)
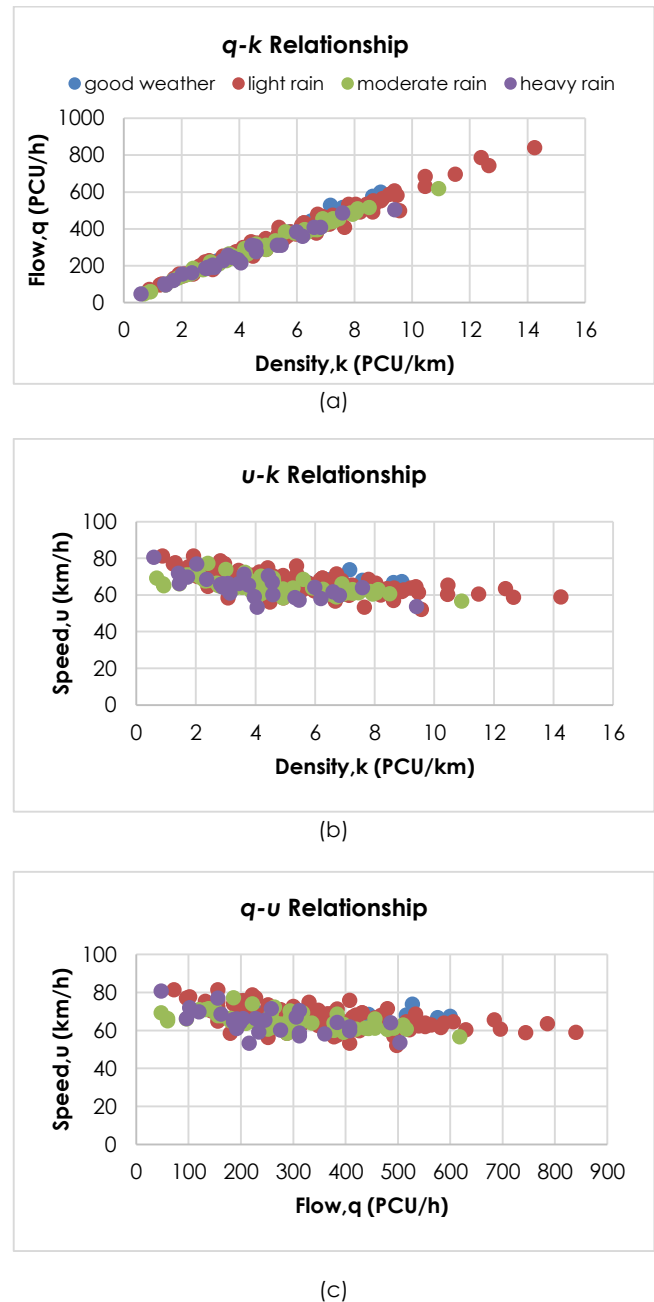
Figure 5 Speed-flow-density relationships for good weather and rainfall conditions

The Greenshield regression equations [1] were then applied to the scatter points in the speed-density, speed-flow and flow-density relationships (Figure 5) for

good weather and each type of rainfall category. The results for the regression analysis are presented in Tables 2, 3 and 4. From the analysis, equations for flow-density relationship show the strongest correlation with R^2 value near to 1.0. However, the relationship for speed-density, and flow-speed showed weaker correlation. Hence, the regression equation for flow-density relationship was chosen to obtain the most important points in fundamental diagram.

Table 1 Speed- flow-density data Statistics for good weather and rainfall conditions

Weather Categories	Mean Flow (PCU/hour)		Mean Speed (km/hour)		Mean Density (PCU/km)		Standard Deviation for Speed (km/h)
	value	change %	value	change %	value	change %	
Good Weather	449.00	Na	68.28	na	6.60	na	3.31
Light Rain	359.38	20.0	66.16	3.1	5.56	15.8	5.91
Moderate Rain	294.95	34.3	64.75	5.2	4.65	29.5	6.13
Heavy Rain	247.60	44.9	63.54	6.9	4.03	38.9	8.54

Table 2 Regression analysis by *u-k* relationship

WeatherCondition	*u-k* Relationship	R^2
Good Weather	$u = 72.274-0.6038k$	0.2466
Light Rain	$u = 73.459-1.3125k$	0.3283
Moderate Rain	$u = 70.744-1.2864k$	0.4693
Heavy Rain	$u = 72.457-2.2125k$	0.4585

Table 3 Regression analysis by *q-u* relationship

WeatherCondition	*q-u* Relationship	R^2
Good Weather	$q = 31.96u-0.3715u^2$	0.1278
Light Rain	$q = 24.044u-0.279u^2$	0.2720
Moderate Rain	$q = 26.754u-0.3414u^2$	0.3470
Heavy Rain	$q = 15.422u-0.1779u^2$	0.3869

Table 4 Regression analysis by *q-k* relationship

WeatherCondition	*q-k* Relationship	R^2
Good Weather	$q = 73.149k-0.723k^2$	0.9864
Light Rain	$q = 70.273k-0.8694k^2$	0.9754
Moderate Rain	$q = 70.211k-1.2032k^2$	0.9908
Heavy Rain	$q = 67.287k-1.2233k^2$	0.9750

According to Ben-Edigbe and Ferguson [23-24], maximum flow where the critical density is reached at the apex point can be computed using flow-density relationship. Consider flow-density equation for good weather:

$$q = 73.149k - 0.723k^2 \qquad (2)$$

By differentiating flow with respect to density, critical density (k_c) can be estimated as:

$$\partial q/\partial k = 73.149-1.446k \qquad (3)$$

$$0 = 73.149-1.446k \qquad (4)$$

Therefore,

$$K_c = 51\ PCU/km \qquad (5)$$

The computed critical density was substituted into equation (2) in order to determine the maximum flow (q_c) forroadway.

$$q_c= 73.149(51) - 0.723(51)^2 = 1850\ PCU/h \qquad (6)$$

By plugging critical density and maximum flow into equation (1), critical speed (u_c) can be obtained:

$$u_c = 1850/51 = 36.27\ km/h \qquad (7)$$

Based on fundamental theory at flow-density curve:

$$k_j = 2(k_c) \qquad (8)$$

Hence, the jam density (k_j) for the roadway can easily be calculated. While the basic equation for the curve is:

$$q = u_f\ k - (u_f/\ k_j)\ k^2 \qquad (9)$$

Thus, by comparing equations (2) and (9), the value for free flow speed (u_f) can be obtained.The results for critical density, maximum flow, critical speed, jam density and free flow speed under good weather and rainfall conditions are summarized in Table 5.

As shown in Table 5, all predicted values decreased as the intensity of rain increased. However for free flow speed, the value fluctuated as the intensity increased. In comparison with good weather, light rain reduced the driver free flow speed by 2.5 km/h. This reduction is lower than free flow speed during moderate rainfall condition even though the intensity of the rainfall is more. The high reduction during light rain condition might be because in the first few minutes after rain begins, the oil and grease on the road has just started to spread over the surface. This slippery surface causes drivers

to drive more slowly. During moderate rainfall condition, the free flow speed increase compared to light rainfall. This may be because the drivers were able to adjust to prevailing condition or the traffic stream had high percentage of drivers with knowledge of the local area [19]. Overall, the finding from this study on important points proved that the curve of fundamental diagram (*q-k* relationship) shrinks with the adverse weather condition as discussed in Section 2.0.

Table 5 Estimated important points derived from flow-density relationship

Weather Condition \ Important Point	Good Weather	Light Rain	Moderate Rain	Heavy Rain
Critical Density, k_c(PCU/km)	51	41	30	28
Maximum Flow, q_c(PCU/h)	1850	1420	1024	925
Critical Speed, u_c(km/h)	36.27	34.63	34.13	33.04
Jam Density, k_j (PCU/km)	102	82	60	56
Free Flow Speed, u_f(km/h)	73.75	71.29	72.19	68.50

5.0 CONCLUSION

This paper presents the traffic flow characteristics under good weather and rainfall conditions in order to better understand speed, flow and density variations and pattern.Analysis and findings on the effect of rainfall on traffic flow characteristics at night under road lighting condition leads to the following conclusions:

i.   Increasing intensity of rainfall has caused reduction to average flow, average speed and average density of roadway up to 44.9%, 6.9% and 38.9%, respectively.

ii.   All the scatter points for speed-density, speed-flow and flow-density relationships fall under uncongested condition. The flow-density relationship has strong regression model as compared to speed-flow and speed-density relationship with $R^2 \approx 1.0$.

iii. The critical density, maximum flow, critical speed, jam density and free flow speed of roadway decrease as the intensity of rain increases. As an implication, the curve of fundamental diagram was shrunk as the intensity of rainfall increases.

Overall, rainfall irrespective of their intensities has impact on traffic flow characteristics of two lane highway in Terengganu.

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