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Effect of Rainfall on Traffic Flow Shock Wave Propagation

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Abstract: This study paper examined the effect of varying rainfall intensity on shock wave formation and propagation. Traffic data were generated from two sites on the J3 and J5 located in Johor and Terengganu States in Malaysia respectively for two months. The two sites were close to surface rain gauge stations. The traffic data were separated into rain and no-rain conditions. The rain conditioned data were further classified as light, moderate or heavy rain. Using the trapezoidal flow contraction technique, the flow rate changes resulting from the effect of rain were determined by comparing the current and capacity states of the traffic stream. The effect of rain on the traffic flow between the current and capacity states were then analysed to see if traffic shock waves will emerge. The results indicate that in all rainy conditions shock waves do not form, instead rarefaction wave form. The speeds of the rarefaction wave for site 1 are 25.36, 23.67 and 24.00 km h^{-1} for light rain, moderate rain and heavy rain respectively. For site 2, the rarefaction wave speeds are 31.67 and 28.25 km h^{-1} for light and moderate rain. The speed and direction of the rarefaction waves are in the direction of the traffic stream and were lower than what will obtain at capacity. The corresponding density changes which trigger the waves are very small. Localized clusters of vehicles restrained by rainfall or inability of vehicles behind the leader to overtake characterize the traffic flow but are not sustained for long periods. This is due to the free-flow conditions of the two facilities with large headways separating vehicle clusters. During peak periods and at bottleneck locations the waves emerging from the influence of rain could turn into shocks and may be more enduring.

Key words: Traffic flow, highway capacity, rainfall intensity, shock wave, propagation.

INTRODUCTION

The impacts of inclement weather conditions on transportation are now widely acknowledged. These include increased risk of accidents, delays, more hazardous driving conditions and general flow disruptions. Flow disruptions caused by rainfall affect both individual vehicles and the traffic stream. The effects on the traffic stream are to cause speed reduction and traffic flow contraction. Traffic flow contraction and speed reduction may cause platoon formation and subsequently bunching of traffic. Two implications of traffic flow bunching are changes in the passenger car equivalents (PCE) of vehicles and traffic flow shock wave generation. Both are the result of instabilities induced by the rainfall. In tropical countries where rainfall is regular and in sufficient quantities, instabilities from rainfall are common and questions have been raised about the appropriateness of the PCE values employed in these conditions. Similarly, the density changes associated with rainfall disturbances require investigation into shock wave propagation under rainfall conditions. To address the impacts of rainfall on traffic flow, it is important to quantify the effects for meaningful strategies to evolve in tackling the problem (Alhassan, 2013).

This study therefore investigates if traffic shock wave is propagated under rainfall as a result of flow contraction. The aim is to see if such waves are detrimental to safe and stable traffic operations under rainfall. The effects of shock wave propagation on traffic flow have been studied variously under normal weather conditions in different traffic contexts but the study is novel under rainfall conditions. The earliest kinematic wave theory was proposed jointly by Lighth and Whitham (1955) and Richards (1956) who worked separately. One important feature of the LWR model as it was later called is its ability to describe the formation of traffic flow shock waves. However, most applications of the model have been centered on congestions from signalised intersections and the inability of the model to detect acceleration-deceleration characteristics of the flows from traffic signals have been a subject of criticism. Along highway segments, the model has been used extensively to explain traffic states and the length of queues that form as a result of flow disturbances. Recently the model has been used in different traffic flow

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contexts. For instance, Wu and Liu (2011) analytically derived the traffic trajectories of four major shock waves such as queuing, discharge, departure and compression waves. Yan *et al.* (2011) also applied shock wave theory to study the impact of large trucks on an expressway. In Slovakia, Kalasova and Krchova (2011) studied the effect of aggressive driving on the formation of congestion using shock wave theory. Also Zhu and Yu (2012) investigated the effects of highway slopes on the stability of traffic flows using the LWR model. In Ngoduy (2011) the continuum theory was applied using the multiclass approach to display the widely scattered flow-density relationship caused by random driver behavior. Again Li *et al.* (2011), used shock wave theory to study the influence of moving bottleneck caused by large trucks in the traffic stream through simulation with VSSIM software. Ramezani and Benekohal (2011) analysed queue formation and dissipation in work zones using the shock wave theory. Suzuki and Matsunaga (2010) evaluated the safety of platooned vehicles based on shock wave theory and (2) examined the onset of congestion due to low-speed merging maneuvers in the traffic stream by use of shock wave theory. The range of applications of shock wave theory on highway segments can therefore be extensive. It can be argued that rainfall which brings about similar traffic flow conditions as slow-moving vehicles and other platooning effects in the traffic stream could invoke the use of shock wave theory.

DATA COLLECTION

Both the J5 and the J3 highways are principal roads which start from Johor Bahru and extend to the north of the Peninsula, were used for data collection in this study. Rain gauge stations were suitably located along them and data obtained from the stations were used in conjunction with the traffic data collected on the facilities. Automatic traffic detectors were then installed to generate traffic data for two months during the monsoon season. The rainfall data were sorted according to intensities and the appropriate traffic data observed under each rain intensity were applied. The traffic data under each rain intensity were analysed separately and compared.

Trapezoidal flow contraction: Trapezoidal flow contraction is derived from the shape of the flow-density fundamental diagram of traffic for two conditions for which flow contraction occurs. Evidence from empirical data suggests that flow-density relationships start from the origin and rise to a single maximum and drops back on the horizontal axis at jam density. For a fundamental diagram with two flow conditions such as no-rain and rain conditions, a typical flow-density plot will be depicted as shown in Fig. 1.

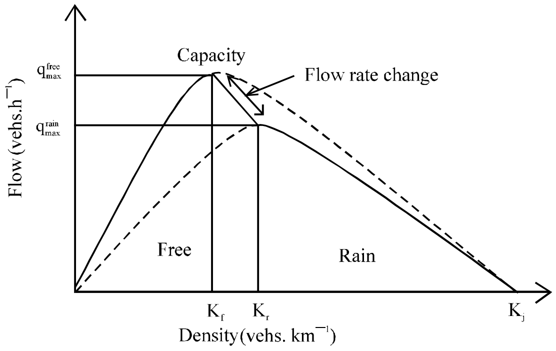

Fig. 1: Fundamental diagram for two flow conditions

The speed-density and the flow-density relations appropriate for determining the traffic states are obtained from Alhassan and Ben-Edigbe (2012) and stated hereunder as Eq. 1 and 2:

$$\mu_s = \mu_f - \frac{\mu_f}{k_j}k \quad (1)$$

$$q = \mu_f k - \frac{\mu_f}{k_j}k^2 \quad (2)$$

where, q is the volume, μ_s is the space mean speed, μ_f is the free-mean speed, k is the density and k_j is the jam density. Equation 1 and 2 are together used to obtain the traffic states on the two facilities. Equation 2 in particular is useful in predicting the capacity of the facility. Comparison of the two traffic conditions of rain and no-rain would reveal if flow contraction has occurred.

Traffic flow shock waves: Traffic Flow shock waves occur when there is an abrupt change in flow density. This sets up an interface at the change point and the traffic flowing into the point decelerate while traffic flowing away from the point may accelerate. The interface movement is the shock wave and points to the rate at which vehicles accumulate behind the discontinuity. For two conditions such as rain and no-rain, the change in traffic state can be shown as in Fig. 2. The shock wave triangle is also shown in Fig. 2 as the dotted coloured line. The resulting shock wave equation is:

$$W_s = \frac{q_{max}^n - q_{max}^r}{k_c^n - k_c^r} \quad (3)$$

where, (q^n_{max}, k_c^n) is the flow and density prior to the rain while (q^r_{max}, k_c^r) is the flow and density due to rain of a particular intensity. Since Eq. 2 is used to predict the traffic state under rainfall, Eq. 3 can be written as

$$W_s = \frac{q^n_{max} - \left\{-\frac{u_f}{k_j}k^2 + u_f k\right\}}{k^n_c - \left\{k^r_c\right\}} \quad (4)$$

Thus Eq. 4 could be used to evaluate the shock wave speed for the three conditions of rain intensity that is light, moderate and heavy rain investigated.

RESULTS AND DISCUSSION

The purpose of this section is to interpret the empirical data and identify features key to the analytical framework to be employed. Examining the effect of rainfall on shock wave propagation implies that rainfall disturbances must not be masked by the occurrence of physical bottlenecks. To be sure that no physical disturbances have occurred at the two sites during data collection, it is pertinent to examine the flow profiles on the two sites during the period. These are shown in Fig. 3 and 4 respectively. The consistency and continuity in the profiles preclude any occurrence of instabilities from physical disturbances. However, the breaks in the observed flows at site 2 are indicative of equipment faults.

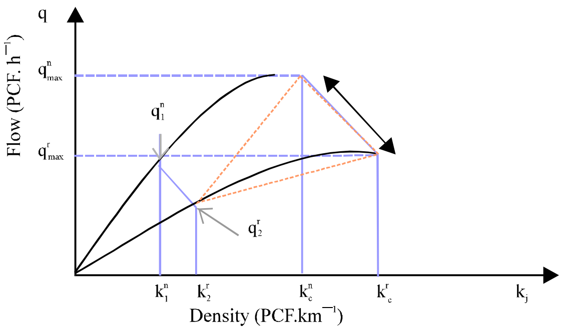

Fig. 2: Shock waves triangle from traffic flow contraction

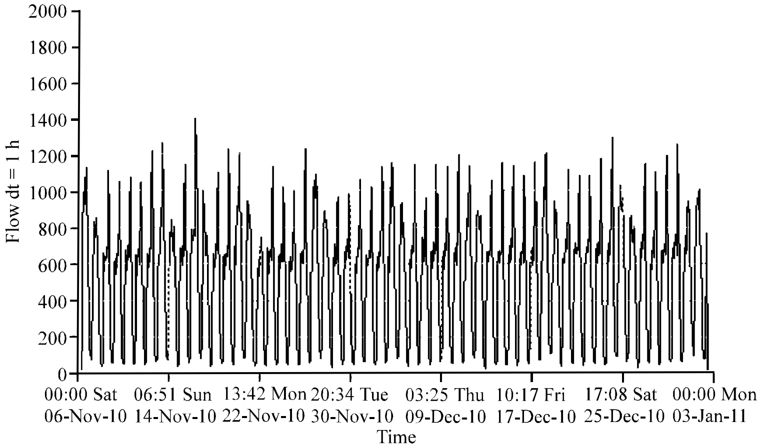

Fig. 3: Traffic flow profile at site 1

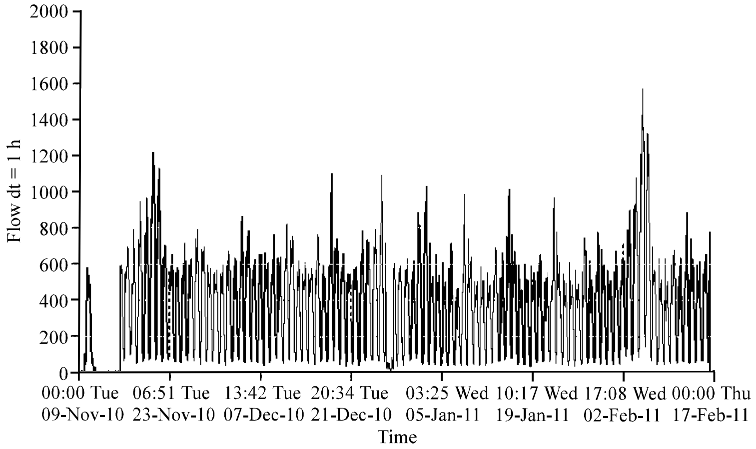

Fig. 4: Traffic flow profile at site 2

Additionally, the two sites have different flow levels. Site 1 has annual daily traffic of 12,000 vehicles while site 2 has 8,000 vehicles. Furthermore, the trends in flow at the two sites show higher flow rates during weekdays than weekends at sites 1 while the reverse is the case in site 2. Site 2 also has many occasional high flows that are difficult to figure out due to unusual patterns of flow.

To evaluate the traffic flow contraction it is pertinent to first determine the traffic states as outlined in section 1.3. The results are shown in Table 1 and 2. The two Table show traffic in both the current and capacity states. The interest is to see what happens at capacity under rainfall conditions since it represents a critical traffic flow state. That is beyond the capacity state, traffic enters into congestion and the instabilities associated with congestion are recursive in nature. Evidently, traffic flow speed decreases as the rain intensity increases as shown by Table 1 and 2. In the current or existing condition, the volumes of traffic do not show a consistent trend. The flow rates are relatively constant suggesting that rainfall is not a hindrance to travel demand. The traffic density follows a similar trend as the flow rates. The density which represents the number of vehicles present per kilometer of roadway is also not affected by rainfall disturbances.

The predicted traffic flow variables were computed at the apex of the curves shown in Fig. 2 and represent the maximum possible flow rates obtainable for the traffic and are called the capacity states. The corresponding speed and density values are needed to completely describe the behaviour of the traffic stream when the road facility is at capacity. Thus for site 1 there were -5.86, -11.40% and-10.82% decreases in volume between the dry weather condition and the rainfall intensities of light, medium and heavy, respectively. The speed changes at capacity as a result of rainfall are -1.89%, -2.25% and -3.78% indicating a decrease of speed as the rain intensity increase. Since speed is an important parameter of traffic at the microscopic level, an increase or decrease of speed will affect the flow rates.

The traffic scenario at site 2 shown in Table 2 reveals lower flow rates at the existing state than was obtainable at site 1. However, the speeds involved are higher and corresponding densities are lower as a result. The predicted traffic scenario indicated at the maximum points of Fig. 2 gave decreasing values of volume as the rainfall intensity increased from light to medium rain. Between the dry condition and the respective rainfall regimes used the volume reductions are 5.02 and 15.70%. As in the case of site 1, the speed values decreased as the rainfall intensity increased resulting in 4.82% decrease between dry weather and light rain condition and 9.04% between dry weather and medium rain condition. The rain intensity category of heavy did not occur at site 2, hence no traffic data was available for analysis. From these tables, one could extract the relevant information to compute the shock wave speed and direction (if any) between the conditions. To proceed, Eq. 4 is called into use and an illustration is given for site 1 as follows:

Table 1: Traffic parameters for site 1 under both dry and rainy conditions

					Percent difference between no rain and		
Parameter	No rain	Light rain	Medium rain	Heavy rain	LR	MR	HR
Current States							
Volume (PCE h^{-1})	683.32	681.09	682.65	681.55	0.33	0.10	0.26
Speed (Km h^{-1})	61.85	60.15	59.23	58.52	2.75	4.24	5.38
Density (PCE km^{-1})	11.13	11.45	11.65	11.77	3.32	4.67	5.75
Capacity States							
Volume (PCE h^{-1})	1569.12	1477.21	1390.24	1400.96	-5.86	-11.40	-10.82
Speed (Km h^{-1})	35.48	34.81	34.68	34.14	-1.89	-2.25	-3.78
Density (PCE km^{-1})	44.22	42.44	40.09	41.03	-4.03	-9.34	-7.21

PCE: Passenger Car Equivalent, LR: Light Rain; MR: Medium Rain; HR: Heavy Rain

Table 2: Traffic Parameters for site 1 under both dry and rainy conditions

					Percent difference between no rain and		
Parameter	No rain	Lightr rain	Medium rain	Heavy rain	LR	MR	HR
Current States							
Volume (PCE h^{-1})	488.24	515.51	411.60	-	5.59	-15.70	-
Speed (Km h^{-1})	74.11	70.12	66.45	-	-5.38	-10.34	-
Density (PCE km^{-1})	6.63	7.46	6.28	-	-12.52	5.28	-
Capacity States							
Volume (PCE h^{-1})	1606.65	1525.82	1270.29	-	-5.03	-20.93	-
Speed (Km h^{-1})	40.70	38.74	37.02	-	-4.82	-9.04	-
Density (PCE km^{-1})	39.47	39.39	34.31	-	-0.20	-13.07	-

PCE: Passenger Car Equivalent, LR: Light Rain; MR: Medium Rain; HR: Heavy Rain

Site 1:

- Dry weather parameters are: Volume = 683.32 pce h^{-1}, density = 11.13 pce km^{-1}
- Light rain parameters are; Volume = 1477.21 pce h^{-1}, density = 42.44 pce km^{-1}
- Medium rain parameters are; Volume = 1390.24 pce h^{-1}, density = 40.09 pce km^{-1}
- Heavy rain parameters are; Volume = 1400.96 pce h^{-1}, density = 41.03 pce km^{-1}

Between dry weather and light rain condition, the wave speed is given by;

$$W_s = \frac{683.32 - 1477.21}{11.13 - 42.44}$$

$$W_s = 25.36 \text{ km h}^{-1}$$

Between the dry weather condition and the medium rain the wave speed is 23.67 while under heavy rain the wave speed is 24.00 km h^{-1}. The results for site 2 are 31.67 and 28.25 km h^{-1} respectively for light and medium rain conditions. The results show that all the wave speeds for the two sites are positive and moving in the direction of the main traffic stream. Unquestionably, kinematic waves are generated from the effect of rain. However, the magnitudes of the kinematic wave speeds for the three rain intensity regimes and the changes in density which occur do not present a shock to the traffic flow. The wave speeds are in the direction of the prevailing traffic flow and lesser in magnitude than the critical speeds at capacity. Thus the wave in the direction of the traffic stream is slower than the stream speed itself at capacity. Also the wave speed decreases as the rain intensity increased for both sites. The implication is that the transition from the traffic flow into the rain-wave front and the discharge away from the rain-wave front is smooth and no detrimental impact on traffic occurs. Once the wave speed becomes equal to or greater than the stream speed the kinematic wave turns into a shock and queues will develop. As long as kinematic wave speed is lower than the speed of the traffic stream at the wave front, rarefaction waves will prevail. The traffic densities at the current state are all less than one-third of the critical densities at capacity. Density changes are the main indicators of backward propagation of the wave front. In view of the free-flow nature on the two facilities, the density changes point to local clusters behind the rain-hindered leader or the cautiousness of the lagging vehicles that caught up with the leader to overtake. Vehicles disperse away from the rain-wave front at higher rates than the accumulation of vehicles behind the rain-wave front. Research on traffic flow shock waves have concentrated on normal weather conditions at bottleneck locations and have tended to evaluate queue lengths rather than velocity of wave propagations. The dissimilarity between this study and others does not warrant a comparison but rather points to the extent to which the shock wave theory could be applied.

CONCLUSION

Traffic flow changes due to rain could generate kinematic waves. The extent to which rain could induce shock waves is dependent on the flow rates and whether the flow is free or constrained.

For unconstrained roadway segments, the kinematic waves will move in the direction of the main traffic stream and rarefaction waves will form.

The effect of the rain is to disperse the flow rather than constrain it. The dispersal increases as the rain intensity increases for the same flow rate.

If the flow rates are sustained at this level, there is no danger of traffic flow hindrances due to rainfall at the capacity state. However, the scenario could be different at higher flow rates.

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