EXPLORING THE EXTENT OF CRITICAL GAP ACCEPTANCE CAUSED BY RAINFALL IN MALAYSIA

Mashros Nordiana, Rahman Raha and Ben-Edigbe Johnnie
Department of Geotechnics and Transportation, Universiti Teknologi Malaysia, Malaysia
E-Mail: edigbe@utm.my

ABSTRACT

At a priority intersection, critical gap is the threshold by which drivers judge whether to accept a gap or retain holding position. It is usually taken as a fixed value or considered to follow a certain distribution. Critical gap is needed at roadway segment to allow road user to make decisions relative to the lead vehicle. If the critical gap is larger than reaction time, drivers maintain safe following distance from the vehicle in front; otherwise the probability of vehicle collusion is heightened. The paper is aimed at determining critical gap acceptance at roadway segment under rainfall condition. Differential gap is expected under dry and rainfall conditions irrespective of rainfall intensity due to reduced visibility. Based on the hypothesis that rainy conditions have effect on critical gap acceptance, impact studies were carried out at Pontian-Skudai Route 5, Malaysia. The objectives are to estimate average gap and determine critical gap acceptance under prevailing conditions. In a 'dry and rainfall impact study', traffic stream gap was calculated from the headway, flow, length of vehicle and speed relationship. Headway was mainly derived from maximum flow rate. Results show that average traffic stream gap for dry weather is higher than that of rainfall conditions. However, motorists maintain a safe following distance under both circumstances. The paper concluded that rainfalls irrespective of their intensities have no significant impact on critical gap acceptance. These so because all observed vehicles on the roadway under rainy conditions are affected and there is no undue advantage enjoyed by any particular type of vehicle.

Keywords: gap acceptance, rainfall, reaction time, headway.

1. BACKGROUND

Rainfall is one of the elements of the weather that may affect traffic flow rate variability. It may be responsible for severe impact on traffic flow due to its spatiotemporal nature. The impacts of these disturbances to the traffic flow are such that the capacity of the highway may become degraded and travel time lost. According to Keay and Simmonds [1] and FHWA [2] the principal problems of rainfall for road traffic are poor visibility, and aquaplaning. Drivers caught up in the rain have been known to reduce speed, increase headways, with resulting contraction in flow [3]. Further, the extent to which flow contraction occurs depends on the intensity of rainfall. According to Hogema [4], Chung *et al.,* [5] and Billot [6] increasing flow contraction will result from increase in rainfall intensity. Since rainfall is assumed to have impact on traffic stream gap, the paper is curious on the extent of gap acceptance. The objectives are; i) to estimate mean gap of a vehicle with and without rainfall under daylight condition, and ii) to compare the mean gaps relative to derivers' reaction times. In the light of the discussion so far, the remainder of the paper has been divided into four sections. In the subsequent section, literatures of gap acceptance are reviewed. In section 3 setup of impact study and data collection process are discussed. Analysis and findings are presented in section 4 and conclusions drawn in section 5.

2. LITERATURE REVIEW

In general, critical gap for a roadway segment is defined by the minimum gap allowable for the road user to react to the lead vehicle. Many research works have been carried out on critical gap acceptance at the priority intersections with scanty works on the issue of gap acceptance along roadway segment. On any roadway segment, critical gaps are taken into consideration before overtaking maneuvers' are done. In circumstances where gaps are well below reaction time, it can be assumed that the probability of accident occurring would be profound. Gap is very similar to headway minus the vehicle length. It is a measure of the time that elapses between the departure of the first vehicle and the arrival of the second at the designated test point. Gap is a measure of the time between the rear bumper of the first vehicle and the front bumper of the second vehicle, where headway focuses on front-to-front times. Gap can be estimated with equation 1 below:

$$g = h - \left(\frac{l}{v}\right) \tag{1}$$

Where

h = headway (s), l = vehicle length (m),

v = vehicle speed (m/s), q = flow (pcu/s).

$$h = {}^{3600}/_{q} \tag{2}$$

Since road theory is concerned with the movement of discrete objects in real time over a network in two dimensions. It can be postulated that any theory incompatible with or independent of the fundamental diagram of traffic is unacceptable. Within the purview of fundamental diagram, it has been shown (13) that:

$$q = -\lambda + ck - ck^2 \tag{3}$$

Where

q = flow, c = coefficients, k = density and
λ = constant

Now if equation (3) is inserted into equation (2), equation (1) can be rewritten as:

$$g = \left(3600 \Big/ -\lambda + ck - ck^2\right) - \left(\frac{l}{v}\right) \tag{4}$$

The minimum safe headway measured tip-to-tail is defined by the braking performance as:

$$T_m = t_r + \frac{kV}{2}\left(\frac{1}{a_f} - \frac{1}{a_l}\right) \tag{5}$$

Where

T_m = minimum safe headway, in seconds
V = speed of the vehicles
t_r = reaction time, the maximum time it takes for a following vehicle to detect a malfunction in the leader, and to fully apply the emergency brakes
a_f = maximum braking deceleration of the follower
a_l = maximum braking deceleration of the leader. For brick-wall considerations
a_l = infinite and this consideration is eliminated
k = arbitrary safety factor, greater than or equal to 1.

The tip-to-tip headway is simply the tip-to-tail headway plus the length of the vehicle, expressed in time:

$$T_s = \frac{L}{V} + t_r + \frac{kV}{2}\left(\frac{1}{a_f} - \frac{1}{a_l}\right) \tag{6}$$

Where: T_s time for vehicle and headway to pass a point and L is the vehicle length

Plug equation (2) and (5) into equation (1) to get the critical gap shown below:

$$g_o = \frac{3600}{(-\lambda + ck - ck^2)} - T_s - t_r\frac{kV}{2}\left(\frac{1}{a_f} - \frac{1}{a_l}\right) \tag{7}$$

The main concern of a driver is to avoid collusion on any roadway section either at a priority intersection or roadway segment. Therefore, an appropriate gap is required for a safe driving. The safe gap is needed because a following driver has to react to the lead vehicle. If a following gap of a vehicle is less than reaction time of a driver, the possibility of collusion is higher. In previous studies driver reaction times vary from 0.5 to 10 seconds across different tasks. Neuman [5] for example, has proposed perception reaction times for different types of roadways, ranging from 1.5 seconds for low-volume roadways to 3.0 seconds for urban freeways. While Green [6] and Summala [7] found that simple human reaction times often less than 1.0 second but decision for this reaction time often takes much longer. In AASHO [8], driver's perception reaction time varies from 0.5 second for simple situations to 4.0 seconds for complex situations and the perception-reaction time in braking is about 2.5 seconds.

In reality, the gap varies for each vehicle depends on many factors such as individual preference for relaxation, time of a day and weather condition among others. In congested traffic, the gap tends to be smaller than in free-flow traffic. Forbes *et al.,* [9] found that the actual time gap varies across driver population and time of a day for an individual driver under rainfall conditions. Previous research works have also shown that motorists adjust their behaviour during rainfall. They overtake less, drive slower and increase their following distance [10] [11]. However, the risk of a crash during rainfall is still far greater than in dry weather. The changes in driving behaviour are apparently, insufficient to compensate for the greater risk during bad weather [12]. In many design manuals reaction time is taken as 2.5s. This is debatable. Green [7] and Summala [8] found that simple human reaction time began as fast as 1 second but decision for this reaction time often takes much longer. However, in driver's perception reaction time varies from 0.5 to 4.0 seconds and the perception-reaction time in braking is about 2.5 seconds [9]. Since reaction time of 2.5s is well established, there is no need to construct a new model on reaction time. What is required is the minimum reaction time that can assumed as 1.5s. In sum, reaction time can said to have a range of 1.5s to 2.5s, it can be argued.

3. DATA COLLECTION

The setup of impact study is shown below in Figure-1. Automatic traffic counters were used to collect 24 hr. traffic data continuously for 6 weeks. The collected data include vehicle speeds, volumes, type of vehicles, headway and gaps. Rainfall data consisted of rain intensity, time and date obtained from the nearest rain gauge station. The federal road was chosen because it connects all states and cities in Malaysia. The data were collected in May-June 2010 during the rainy season. The rainfall classification was based on the World Meteorological Organization (WMO) Scheme. The categories are: 1) dry; 2) light rain ($i < 2.5$ mm/hr); moderate rain ($2.5 \leq i < 10.0$ mm/hr); and heavy rain ($10.0 \leq i < 50.0$ mm/hr). Rainfall in excess of 50mm/hr is not classified.

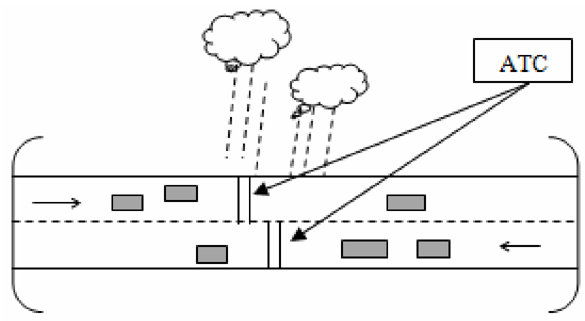

Figure-1. Setup of impact study

4. EMPIRICAL FINDINGS

The composition of motorcycles and cars were 11.8% and 77.2%, respectively in the traffic stream. While the light goods vehicles, moderate goods vehicles and heavy goods vehicles were 4.5%, 3.1% and 3.3% respectively and buses at 0.1%. Table-1 below shows the summary of parameters used in determining gap under the prevailing traffic condition. Assumption that the average passenger car length is 4.12 m, there is no specific pattern for the average maximum flow rate for all conditions as they are in free flow condition; however it was observed that at the 85th percentile, speed reduction was significant between dry to heavy rainfall conditions.

Table-2 presents the gap acceptance statistics under the prevailing traffic condition. The minimum gaps for dry, light rain and moderate rain are more than 3 second, but for the heavy rain the minimum gap found was less than 3 seconds. In order to compare mean gap under dry and rainfall conditions, the χ^2-test was performed with the hypothesis below. Results indicate that the null hypothesis at 95% confidence level was accepted for dry and rainfall conditions, which suggested that difference was not statistically significant. It was found that the mean gaps for all conditions are greater than the most reaction times being, which is between 1.5 and 2.5 seconds. This signifies that the vehicles are in safe following distance. Even though the worst gap was taken into account; the drivers still maintain the safe following gap.

Table-3 provides the estimated flow-density model equation that was used to estimate capacity, optimum speed and critical density as shown in Table-4. In general, capacities and optimum speeds decrease when weather change from dry to heavy rain, however it can be seen that the critical densities for rainfall increase more than critical density under dry condition. This indicates that the capacities for rainfall condition were in congestion. From the table, it was found that the gap for dry condition is 1.78s. When the rain falls, gaps increase with increase in rainfall intensity. This implies that motorists increase their following distance during rainfall. Although the gap increases due to rainfall, the clearance decreases as it influenced by speed and headway.

Table-1. Mean gap under the prevailing traffic condition.

Condition	**Average maximum flow rate** (pce/hr)	**Average speed** (km/hr)	**Average density** (pce/km)	**85th percentile speed** (km/hr)	**Hwy** (s)	**Spacing** (m)	**Gap** (s)	**Clearance** (m)
Dry	774	64.7	12.0	68.0	4.65	83.57	4.43	79.45
Light rain	734	62.6	11.7	64.8	4.90	85.21	4.67	81.09
Moderate rain	780	59.7	13.1	63.6	4.62	76.62	4.39	72.50
Heavy rain	853	53.7	15.9	57.4	4.22	62.95	3.96	58.83

Note: Hwy-headway

Table-2. Gap acceptance statistics under the prevailing traffic condition.

Condition	**Mean Gap** (s)	**Standard Dev.** (s)	**Standard tolerance** (s)	**p-value**	**Reject hypothesis Null?**	**Comment**	
						RT = 1.5s	**RT = 2.5s**
Dry	4.43	1.02	3.41	-	-	Safe	Safe
Light rain	4.67	1.07	3.60	0.909	No	Safe	Safe
Moderate rain	4.39	0.85	3.54	0.984	No	Safe	Safe
Heavy rain	3.96	1.01	2.95	0.823	No	Safe	Safe

Note: RT - Reaction Time; H_0: $\mu_{\text{without rainfall}} = \mu_{\text{with rainfall}}$; H_1: $\mu_{\text{without rainfall}} \neq \mu_{\text{with rainfall}}$

Table-3. Estimated flow-density model equation.

Condition	Model Equation	R^2
Dry	$q= -1.117k^2 + 90.23k -138.5$	0.966
Light rain	$q= -0.944k^2 + 79.10k -60.42$	0.964
Moderate rain	$q= -0.911k^2 + 78.03k -80.61$	0.858
Heavy rain	$q= -0.747k^2 + 67.79k -28.86$	0.979

Table-4. Mean gap under the expected capacity.

Condition	Capacity (pce/hr)	Optimum speed (km/hr)	Critical density (pce/km)	Headway (s)	Spacing (m)	Gap (s)	Clearance (m)
Dry	1684	41.7	40	2.14	24.79	1.78	20.67
LR	1597	38.1	42	2.25	23.81	1.86	19.69
MR	1590	37.1	43	2.26	23.29	1.86	19.17
HR	1509	33.3	45	2.39	22.11	1.94	17.99

Note: LR-light rainfall; MR-moderate rainfall; HR-heavy rainfall

Table-5. Gap acceptance statistics under the expected capacity.

Condition	Mean gap (s)	p-value	Comment	
			RT = 1.5s	RT = 2.5s
Dry	1.78	-	Safe	Unsafe
Light rain	1.86	0.952	Safe	Unsafe
Moderate rain	1.86	0.952	Safe	Unsafe
Heavy rain	1.94	0.904	Safe	Unsafe

Note: RT - Reaction Time

The χ^2-test was used to determine the significant of mean gap between dry and rainfall conditions under predicted capacity and the results are shown in Table-5. The null hypothesis at 95% confidence level was accepted for all conditions, which suggested that difference was not statistically significant. Comparison with the reaction times also shown that the mean gaps are more than 1.5 seconds but still less than 2.5 seconds. If a driver has 1.5 seconds reaction times, it is clear that the mean gap under dry and rainfall condition is acceptable as safe following distance. When the reaction time is 2.5 seconds, which is bigger than the mean gap, the spacing is not enough for driver to avoid collusion. So it is considered as a dangerous follow-up distance. From the results, it is clear that the mean gaps change under different rainfall condition.

Findings from the paper have shown that the mean gaps for dry and rainfall conditions under the free flow traffic condition are more than 4.0 seconds, except for heavy rainfall condition. However, when the road is at capacity, the mean gaps fall in between 1.0 to 2.0 seconds. Statistical results have shown that there is no significant difference between mean gaps under dry and rainfall conditions. There is a separation problem with gap at capacity; one is not certain about the precise contributions of peak hour factor and rain conditions.

5. CONCLUSIONS

The paper is aimed at determining critical gap acceptance at roadway segment under dry and rainfall conditions. Average gap and critical gap acceptance under prevailing conditions were determined. Results show that average traffic stream gap for dry weather is higher than that of rainfall under free flow conditions. The paper concluded that rainfalls irrespective of their intensities have no significant impact on mean gap acceptance of highway traffic stream under free flow condition. Therefore, the hypothesis that rainfall intensity has effect on free-flow mean gap acceptance is null and void. And also that, rainfalls, irrespective of their intensities have no significant impact on critical gap acceptance. This so because all vehicles on the roadway under rainy conditions are affected and there is no undue advantage enjoyed by any particular type of vehicle.

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