Impact of Rainfall on Multilane Roundabout Flowrate Contraction

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Abstract. In this study, roundabouts at two sites in the Malaysia were investigated under rainy and dry weather conditions. Two automatic traffic counters per roundabout arm as well as two rain gauge stations were used to collect data at each surveyed site. Nearly one million vehicles were investigated at four sites. Vehicle volume, speeds and headways for entry and circulating flows were collected continuously at each roundabout arm for six weeks between November 2013 and January 2014. Empirical regression technique and gap-acceptance models were modified and used to analyze roundabout capacity. Good fits to the data were obtained; the results also fit models developed in other countries. It was assumed that entry capacity depends on the geometric characteristics of the roundabout, particularly the diameter of the outside circle of the intersection. It was also postulated that geometric characteristics determine the speed of vehicles around the central island and, therefore, have an impact on the gap-acceptance process and consequently the capacity. Only off-peak traffic data per light, moderate or heavy rainfall were analysed. Peak traffic data were not used because of the presence of peak traffic flow. Passenger car equivalent values being an instrument of conversion from traffic volume to flow were modified. Results show that, average entry capacity loss is about 22.6% under light rainfall, about 18.1% under moderate rainfall and about 5.6% under heavy rainfall. Significant entry capacity loss would result from rainfall irrespective of their intensity. It can be postulated that entry capacity loss under heavy rainfall is lowest because the advantage enjoyed by circulating flow would be greatly reduced with increased rainfall intensity. The paper concluded that rainfall has significant impact of flowrate contraction at roundabouts.

1. Introduction
Rainfall is the quantity of water precipitated as rain in a specified area and for a given time period. It can be heavy, moderate or light. Rainfall intensity is classified according to the rate of precipitation, when the precipitation rate is < 2.5 mm per hour it is classified as light, moderate when the precipitation rate is between 2.5 mm - 10 mm per hour, heavy when the precipitation rate is between 10 mm and 50 mm per hour. Rainfall intensity greater than 50 mm per hour is classified as very heavy and not investigated in this study. Rain shower irrespective of their intensity reduces visibility and sight distance. Since rain shower covers the entire site under observation, it can be mentioned that visibility and sight distance reduction will affect vehicles at both entry and circulating flow. That begged the question; how would traffic flow operation be affected under rain shower condition. Would
it be any different from dry weather condition? The paper would investigate the extent of traffic flow contraction at standard roundabout under rain shower condition.

According to the highway capacity manual (HCM, 2010), the roundabout is the type of unsignalized intersection and is described as “intersections with a general circular shape, characterized by yield on entry and circulation around a central island” [1]. Roundabouts have significant characteristics because they designed to minimize traffic conflicts and make intersections safer and more efficient for users. There are many roundabouts in the Malaysia. Majority of them are multilane and located in the urban areas and on federal route intersections. In Kuala Lumpur, capital city of Malaysia, the vast majority of roundabouts can be found at the radial and ring roads intersections. Most of the roundabouts are essentially at grade [2]. Methods used for roundabout capacity, performance and level of service analysis are traditionally classified into gap-acceptance based methods and linear-regression based methods. The U.S. roundabout capacity formulae are based on research from National Cooperative Highway Research Program (NCHRP) Report 572. The capacity of a roundabout entry was found to be a function of one flow variable, circulating flow in a negative exponential regression equation. This differs from Transport Research Laboratory, United Kingdom findings which revealed that a linear relationship with substantive geometric sensitivity. The issue of substantive geometric design of roundabout cannot be ignored; probably that explains why HCM 2010 developed single lane and multilane linear regressions to differential capacity performance of single lane roundabout from multi lane roundabout. It can be argued that, without geometric sensitivity other than number of lanes, analysts and designers will not have all the tools necessary to develop robust roundabout designs. Since HCM 2010 roundabout capacity procedure has no geometric variation, this paper relied on a alternative analytical techniques adapted from the U.K. empirical model. In any case previous models have no passenger car equivalent values modification capability which is introduced in this paper. The remainder of the paper consists of literature review impact study setup and data collection as well as results, discussion and conclusion in that order.

2. Literature review
Geometric-sensitivity is an empirical model requirement that can be fine-tuned to prevailing conditions. Without the capability to predict different capacities for a variety of configurations, researchers run the risk of over estimations, decreasing safety and increasing conflicts. It can be argued. According to Lenters and Clayton [16], the U.K. model and the related procedure for calibrating it to local conditions are feasible for U.S. roundabouts when sites that experience design year flows are more numerous. According to Akcelick [17] the UK linear regression model underestimates capacity for low circulating flow rates and overestimates capacity for high circulating flow rates by its nature, i.e. being a linear regression model, especially as it reflects the peculiar geometric designs of UK roundabouts included in the capacity database. Based on these previous studies, it can be argued that a modified UK model has a global appeal.

Previous studies on roundabout focused mainly on dry weather and darkness traffic performance at roundabouts without impact study [3-5]. Burrow [3] concluded that the capacity of the junction declined by 5% in dark condition. Billot et al. [9] studied the impact of rainfall on traffic operation and concluded that rainfall reduces headways, speed and flow considerably [9]. Ben-Edigbe [10] also studied the highway capacity under poor weather condition and concluded that road capacity decrease due to increase in the adverse weather conditions as well as heavy rainfall caused capacity loss on the highway. G. Tenekeci, F. Montgomery and S. Wainaina [11] studied the entry capacity of at-grade roundabout during adverse weather condition and concluded that wet and dark conditions have significant impact of the entry capacity of urban at-grade roundabout. Entry capacity loss by 14% under dry-dark, 17% under wet-light, and 25% under wet-dark conditions. According to Transportation Research Board [1, 6], roundabout capacity is defined as the maximum sustainable traffic flowrate that can be achieved during a specified time period under prevailing road, traffic and control conditions. However, all previous studies used the same passenger car equivalent values for all conditions. This cannot be correct because traffic flow is a function of prevailing road, traffic and
weather conditions, therefore passenger car equivalent values must also be modified relative to prevailing conditions. It can be argued that modification would have insignificant impact on the study outcomes, nonetheless modification is a procedure that cannot be ignored or assumed to be insignificant. In this paper, passenger car equivalent values were modified to take into account prevailing weather condition. As contained in many literatures and rightly so, three parameters namely: circulating flow, entry flow as well as the geometry of the roundabout are used to illustrate the operational aspects of any particular roundabout system. Fig.1 presents the observed relationships among these significant aspects. The flow is the amount of vehicles that traverse at given point or section in a unit of time. Circulating flow is the number of flows on circulating approach while the entry flow is quantity of vehicles in the entry approach. The effect of entry width is used to determine the intercept of the capacity equation which was developed based on the simple linear regression.

\[
Q_e = k(F-\frac{Q_c}{Q_e})
\]

(1)

where, \(Q_e\) denotes entry capacity\(l\) and \(Q_c\) denotes circulating flow.

In Malaysia, the design of roundabout is categorized depending on the size of inscribed circle diameters and consists of conventional, small as well as mini roundabout [14]. In the conventional roundabout, the weaving movement is between two entries of a roundabout. In addition, Arahan Teknik (J) 11/87 used the differential equations in each size of the roundabout to evaluate their capacity. Table 1 below illustrates the size of each type of the roundabout based on Malaysian guideline. Fig. 2 is a typical conventional roundabout.
Table 1 Distinction of Roundabout Sizes

|                | Diameter of Inscribed Circle [m] | Diameter of Centre Circle [m] |
|----------------|---------------------------------|------------------------------|
| Conventional   | $D_I > 50$                       | $D_C > 25$                   |
| Small          | $50 > D_I > 20$                  | $25 > D_C > 4$               |
| Mini           | $20 > D_I$                       | $4 > D_C$                    |

Source: [Arahan Teknik (J) 11/87]

3. Rainfall Intensity and Distribution in Malaysia

Malaysia has high-ranking of rainfall, which is usually regular. There are not many locations within Malaysia having a lot less than 2450 mm annual rainfall. The highest amount of rainfall is at the highlands of Sabah and Sarawak with 4064 mm rain annually and the lowest in northern Kedah and Perlis with 1254 mm rain annually. The North-East monsoon, starts from November to February with approximately 150 mm rain per day. Rainfall intensity is defined as the quantity of rainfall per unit of time. Rain gauge is used to measure the amount of rainfall in millimeters per day or hour. The size of rainfall is usually linked to the intensity of rainfall. Table 2 below illustrates the intensity of rainfall category [13].
Table 2. Rainfall Intensity Category

| Rainfall Category       | Intensity [hr] |
|------------------------|----------------|
| Light Rain             | < 2.5 mm       |
| Moderate Rain          | 2.5 - 10 mm    |
| Heavy Rain             | 10 - 50 mm     |
| Very Heavy Rain        | > 50           |

Source: World Meteorological Organizations

4. Impact Study Setup and Data Collection
A shortlist of 50 roundabouts on the federal road in the Malaysia was considered from which two survey sites with the same geometric configurations were selected. The survey sites consist of two-lane roundabout and situated along federal road number 50, which is a significant road that connects the Batu Pahat to the Mersing Jemaluang. This road is the main trunk road of the west coast of Peninsular Malaysia. The Annual Average Daily Traffic Volume (AADT) is approximately 15000 to 20000 vph. This federal road is categorized as a paved federal road and it is under the authority of Public Work Department Malaysia. Automatic traffic counters (ATC) were set-up to collect the required traffic flow data at the roundabout in close proximity to a rain gauge station (RGS) as shown below in fig. 3. Entry and circulating vehicle volume were collected continuously for six weeks under dry and rainfall conditions. Supplementry information like headway, speed gap and vehicle types were also collected. Six classes of vehicles were recognized, namely: Private Car, Motorcycle, Van, medium Lorries, Bus as well as heavy Lorries. The sample survey was done between November 2013 and January 2014.

![Fig.3 Typical Setup of Impact study](image)

5. Results and Discussions
Table 3 presents the summary of survey sites. The information in table 3 were used to modify F and fc linear regression values in Eq 1. The modification was needed so that the ensuing empirical regression model would reflect driving behaviour at roundabout in Malaysia. Note also that the passenger car equivalent values shown in table 4 were also modified to reflect prevailing conditions. This is a clear departure from approaches used in previous studies.

| Table 3, Summary Sheet of Survey Sites |
|----------------------------------------|
| Feature                  | Site 1     | Site 2     |
| Type of Roundabout        | At-grade   | At-grade   |
| Surfacing Type            | Asphalt    | Asphalt    |
| Provision of Road Drainage| Yes        | Yes        |
Facility

| Facility                                      | 1.2 | 1.2 |
|----------------------------------------------|-----|-----|
| Distance to Rain Gauge Station (km)          |     |     |
| Rain Gauge Station Number                    | 2033152 | 2033152 |
| Approach Half Road Width (m)                 | 6.5 | 6.5 |
| Entry Width (e₁) (m)                         | 9.5 | 11.5 |
| Effective Flare Length (m)                   | 15  | 15  |
| Entry Radius (m)                             | 21  | 15.3 |
| Entry Angle (m)                              | 45  | 45  |
| Circulating Stream Width (m)                 | 11.30 | 11  |
| Inscribed Circle Diameter                    | 50  | 50  |
| Length of Weaving Section (m)                | 37  | 35  |
| Circulating road width, e₂                   | 7.5 | 7.5 |
| Width of weaving Section                      | 9.50 | 8.50 |

Note: to be read in conjunction with Fig. 1

Table 4. Modified and Malaysian PCE Values

| Vehicle Type         | No Rain | Light Rain | Moderate Rain | Heavy Rain | Malaysian PCE’s |
|----------------------|---------|------------|---------------|------------|-----------------|
| Passenger Car        | 1.0     | 1.0        | 1.0           | 1.0        | 1.0             |
| Light Vans           | 1.1     | 1.1        | 1.2           | 1.2        | 2.0             |
| Medium Lorry         | 1.1     | 1.2        | 1.2           | 1.3        | 2.8             |
| Heavy Lorry          | 1.1     | 1.2        | 1.3           | 1.3        | 2.8             |
| Bus                  | 1.2     | 1.3        | 1.2           | 1.4        | 2.8             |

In Table 4 passenger car equivalent values were modified for rainfall conditions. Rather than use the Malaysian pce values for dry weather conditions, they were modified as well so that an acceptable comparisons can be made. In any case under rainfall conditions, modified pce values suggest that passenger cars have small advantage on other vehicle types. This is not the case with Malaysian pce values that suggest that passenger cars have twice as much advantage over light van and almost thrice as much over other types of vehicle at roundabouts. Therefore are must be taken when using passenger car equivalent values to convert traffic volumes to flows.

The modified linear regression method used in the paper was based on TRL capacity estimation method. Based on Eq.1 where \( Q_e \) is as the dependent and \( Q_c \) is as the independent variable and \( F \) and \( f_c \) are constants as hown below in table 5. Note that high circulatin flow triggers low entry flow and low circulatin flow triggers high entry flow at all sites. Note also that the coefficient of determination \( R^2 \) is greater than 50% at all sites thus suggesting that ensuing model equations can be used to predcit entry capacity. Also that F test are greater than 4 suggestig that the model did not happen by chance. As show in Tables 6 and 7, entry capacity decreased from 1842 pcu/h under dry weaher condition to 1444 pcu per hour under heavy rainfall at sites 1. At site 2 entry capacity decreased from 1795 pcu per hour under dry weather conditions to 1369 pcu per hour under heavy rainfall condition.

Table 5. Summary of Entry Flow and Circulating Flowrate (pcu/hr)

| Site | No Rain Entry (pcu/h) | Circulating (pcu/h) | Light Rain Entry (pcu/h) | Circulating (pcu/h) | Moderate Rain Entry (pcu/h) | Circulating (pcu/h) | Heavy Rain Entry (pcu/h) | Circulating (pcu/h) |
|------|----------------------|---------------------|-------------------------|---------------------|-----------------------------|---------------------|--------------------------|---------------------|
| Site 1| 1192                | 577                 | 1117                    | 582                 | 889                         | 579                 | 1046                     | 610                 |
| Site 2| 550                 | 804                 | 691                     | 805                 | 802                         | 985                 | 529                      | 815                 |
Table 6. Summary of the Regression Analysis on Site 1

| Condition   | No Rain | Light Rain | Moderate Rain | Heavy Rain |
|-------------|---------|------------|---------------|------------|
| Slope       | -1.32711| -1.16078   | -1.20181      | -0.90416   |
| Intercept   | 1842.355| 1682.138   | 1583.417      | 1444.937   |
| R²          | 0.53    | 0.55       | 0.59          | 0.56       |
| F-test      | 9.4     | 8.5        | 6.4           | 9.6        |
| t-test      | 3.06    | 4.6        | 2.5           | 3.1        |

Table 7. Summary of the Regression Analysis on Site 2

| Condition   | No Rain | Light Rain | Moderate Rain | Heavy Rain |
|-------------|---------|------------|---------------|------------|
| Slope       | -1.55041| -1.27304   | -0.60409      | -1.03321   |
| Intercept   | 1795.711| 1750.294   | 1395.885      | 1369.851   |
| R²          | 0.52    | 0.56       | 0.7           | 0.54       |
| F-test      | 13.5    | 4.5        | 8.6           | 8.04       |
| t-test      | 3.6     | 2.1        | 4.9           | 2.8        |

Table 8. Entry-Circulating Flow Relationship during No-Rain and Rain Conditions

| Condition   | No Rain | Light Rain | Medium Rain | Heavy Rain |
|-------------|---------|------------|-------------|------------|
| Site 1      | $Q_e = -1.33Q_c + 1843$ | $Q_e = -1.16Q_c + 1683$ | $Q_e = -1.2Q_c + 1584$ | $Q_e = -0.9Q_c + 1445$ |
| Site 2      | $Q_e = -1.55Q_c + 1796$ | $Q_e = -1.27Q_c + 1750$ | $Q_e = -0.6Q_c + 1396$ | $Q_e = -1.03Q_c + 1370$ |

From table 8, the difference in roundabout entry capacity under different rainfall intensity can be summarised as: Site 1: Light Rain: (1843-1683)= 160 (pcu/hr) or 8.7%; Moderate Rain: (1843-1584)= 259 (pcu/hr) or 14.1%; and Heavy Rain: (1843-1445)= 398 (pcu/hr) or 21.6%. Site 2: Light Rain: (1796-1750)= 46 (pcu/hr) or 2.6%; Moderate Rain: (1796-1396)= 400 (pcu/hr) or 22.2% and Heavy Rain: (1796-1370)= 426 (pcu/hr) or 23.7%. When the circulating flow is at zero, there was significant reduction in entry capacity attributed to heavy rain where the intensity is between 10 to 50 millimeters per hour with a range of 21.6-23.7%. As for moderate rainfall 14.05 – 22.2% reduction in entry capacity was estimated whereas light rainfall, has a range of about 2.6-8.7%. Although not the focus of this paper, it can be postulated that the reasons attributed to these entry flowrate contraction may include poor visibility and reduced sight distance among others.

6. Conclusion
In this paper, flowrate contraction under various rain conditions were compared with the no-rain condition. Rainfall was classified into three categories as light with the intensity of rainfall less than 2.5 mm per hour, moderate when the intensity of rainfall is between 2.5 and 10 mm per hour and heavy with the intensity of rainfall between 10 and 50 mm per hour and it represents the amount of rain that has occurred at locations during observations periods. Roundabout capacity was defined as the maximum sustainable flow rate that can be achieved during a specified time period under prevailing road, traffic and control conditions. Modified TRL capacity method was relied upon because it relates traffic flow to roundabout geometric design. Malaysia passenger car equivalent values were modified. Based on the synthesis of evidences obtained from the relationship between roundabout capacity loss and rainfall, it is correct to conclude that entry and circulating speed and roundabout capacity decreases with increasing of rainfall intensities. Whilst the outcomes of moderate and heavy rainfalls show consistency light rain outcome is inconclusive. In sum the study has shown that: i) entry flowrate reduction would result from rainfall; ii) pee values can be modified relative to
prevailing conditions; iii) linear relationship exists between entry flow contraction and rainfall; and iv) heavy rainfall is a significant contributor to roundabout capacity loss.

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