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# A QUALITATIVE PERFORMANCE ANALYSIS OF ROTARY INTERSECTIONS IN AN URBAN METROPOLIS, NIGERIA

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**Abstract:** Assessment of the qualitative performance of a roundabout in relation to factors, such as delays, queues, level of service (LOS), accident, operation cost and environmental issues is necessary for its successful operation. This study, therefore, aims at analysing the qualitative performance of roundabouts in an urban area, Nigeria with the Fate roundabout in Ilorin metropolitan city as study case. The movement of the vehicles was observed and traffic counts carried out manually, at 15 minutes intervals for 12 hours (6:30am-6:30pm) daily for seven (7) days, from Monday, June 15th to Sunday, June 21st, 2015. Results show that, the five (5) working days (Monday-Friday), have high traffic volume counts and were selected for the analysis. Peak hour factors (PHF) were used to convert the demand volumes to flow rates. The qualitative performance analyses were carried out based on the 12-step approach for the performance analysis of a roundabout as outlined by the Highway Capacity Manual. Approach and entry capacities were determined as mathematical functions of critical headway, and follow-up headway were then estimated using the analytical approach. The degree of saturation, delay, and queue length used in estimating the performance of a roundabout were also determined. The relation between the roundabout performance measure and capacity, expressed in terms of degree of saturation shows that the performance of the Fate roundabout ranged between LOS A – E. An increase in the entry lane width at Basin road approach was recommended to ensure continuous and smooth flow at the roundabout.

**Keywords:** *Roundabout, level of service, entry capacities, peak hour factor, volume rates*

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## 1.0 Introduction

Qualitative performance analysis of a roundabout is very important since it is directly related to delay, queues, level of service, accident, operation cost, and environmental issues. For more than three decades, modern roundabouts have been used successfully throughout the world as a junction control device. Nigeria also has its share of roundabouts. Three performance measures are typically used to estimate the performance of a given roundabout design: These are: (i) degree of saturation (ii) delay, and (iii) queue length. Each measure provides a unique perspective on the quality of service, at which a roundabout will perform under a given set of traffic and geometric conditions (Rodegerdts *et al*., 2010).

Transport Research Laboratory (TRL) of England first introduced modern roundabout facilities in the early 1960s in the United Kingdom. These facilities were introduced in order to solve the problems of the existing rotaries and traffic circles, using the principle that entering traffic yields to circulating traffic, or the "give way" rule, and almost all city planners soon accepted it. Above all, improvement in safety is the most distinct advantage of roundabouts. Most areas that implement roundabout rules experienced an impressive reduction impact on their accident numbers. Due to this reputation, some countries converted many ordinary intersections into roundabouts (Mark, 2003). Contingent on the operational situations, there are copious merits that roundabouts have compared to traffic signals (Akçelic, 2011). Roundabouts provide better safety than other schemes of traffic controls (Sargeant and Christie, 2002). They reduce crash severity as head-on as well as right-angle conflicts are almost removed and can handle higher volume of traffic with less delay compared to signalized control intersections. They probably use less area of land as turn pocket lanes are not required. Furthermore, they provide superior energy and maintenance costs compared to other intersection treatments (DeAmico, 2012). Nonetheless, their successful design and operation depend largely on communication and quality engineering. They are as well influenced by public opinions and driver education (Churchill *et al*., 2010). Highway Capacity Manual (HCM, 2010) presented models, used for the analysis and determination of capacity of roundabouts, are viewed as (i) exponential regression (empirical) models and (ii) gap-acceptance (analytical) models.

HCM (2010) presents roundabout capacity (pc/h) model for both single and multi-lane roundabout entries for both *empirical* and analytical approaches as;

$$C_e = A\exp(-Bq_c) \quad (1)$$

where; $C_e$ = Entry lane Capacity of roundabout, $q_c$ is the conflicting (opposing) flow rate in pc/h which is the circulating flow rate upstream of the subject entry and, parameters $A$ and $B$ are respectively defined as the follow-up headway and critical headway values, expressed as:

$$A = \frac{3600}{t_f} \quad (2)$$

$$B = \frac{(t_c - 0.5t_f)}{3600} \qquad (3)$$

where; $t_f$ = follow-up headway (secs) and $t_c$ = critical headway (secs)

The quality of service is the measure of smooth operation of a transportation facility from a traveler's perspective, whereas LOS is the quantitative stratification of the performance measure that represents the quality of service (HCM, 2010). For roundabouts, LOS was defined using control delay with criteria given in Table 1. LOS F is assigned if the volume-to-capacity ratio of a lane exceeds 1.0 regardless of the control delay. For assessment of LOS at the approach and intersection levels, LOS is based solely on control delay.

Table 1: Level-of-Service Criteria

| *Control Delay (sec/veh)* | *Level of Service by Volume-to-Capacity Ratio** | |
|---|---|---|
| | *v/c ≤ 1.0* | *v/c > 1.0* |
| 0 – 10 | A | F |
| >10 – 15 | B | F |
| >15 – 25 | C | F |
| >25 – 35 | D | F |
| >35 – 50 | E | F |
| >50 | F | F |

*For approaches and intersection-wide assessment, LOS is defined solely by control delay (Source: HCM, 2010)

This study aims at assessing the qualitative performance of roundabouts in an urban metropolis using the Fate roundabout in Ilorin, Nigeria as a study case. The Fate roundabout receives traffic from four important legs namely (a) Basin Road, which links the Lower Niger River Basin Development Authority employing hundreds of citizens, (b) Tanke Road, which collects traffic from high density residential area, (c) Umar Audi Road, which links the Government offices and Government Residential Areas, and (d) Fate Road on which the Federal Secretariat, housing all federal ministries with thousands of federal workers, is located. The facilities on the roundabout require upgrading to meet the demand of the ever-growing traffic to prevent the roundabout from performing at an unacceptable level of service. The objectives are to (i) carry out traffic studies and determine the geometric parameters of the Fate roundabout, (ii) compute the capacity of the roundabout using the Analytical (Gap-Acceptance) method and determine the degree of saturation, delay, and queue lengths at the roundabout, (iii) determine the qualitative performance based on level of service (LOS) of the roundabout, and hence (iv) make necessary recommendations.

## 2.0 Methodology

### *2.1 Description of Study Area*

Fate Roundabout is located in Ilorin metropolis, which is on longitude N 8°29'39'' and latitude E 4°35'40'' (CIA, 2013; Nokia HERE Maps, 2015). Figure 1 shows the location of the study roundabout. The north-bound leg is the Basin Road (Approach 1), the east-bound is the Tanke Road (Approach 2), the south-bound leg is the Umaru Audi Road (Approach 3), and the west-bound leg is the Fate Road (Approach 4). The study area comprises of administrative, commercial and residential activities.

### *2.2 Data Collection*

Two enumerators each were put at strategic locations at each of the four arms of the roundabout and traffic data was manually collected. Vehicle type and all the turning movement counts for left-turn (LT), through (TT) and right-turn (RT) were conducted at 15 minutes intervals using count sheet forms. Vehicle type and turning movement counts were done between 6:30 am to 6:30 pm daily for Seven (7) days (Monday, 15th June, 2015 – Sunday, 21st June, 2015) to capture the peak and off-peak periods for the vehicular movements in order to achieve the objective of the study. During the course of the count, it was observed that the highest volume of vehicles was recorded between 7:30 am and 8:30 am, and the lowest vehicular volumes were recorded between 12:00 pm and 1:00 pm. From the seven-day count, the five (5) working days (Monday to Friday) which produced the highest counts recorded were selected for the analysis. The existing dimensions of Fate roundabout is presented in Figure 2.

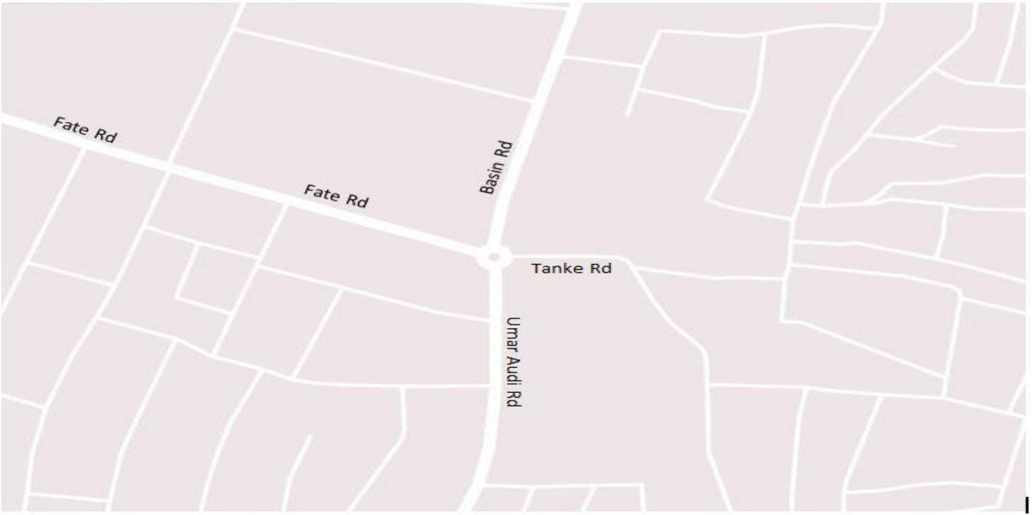
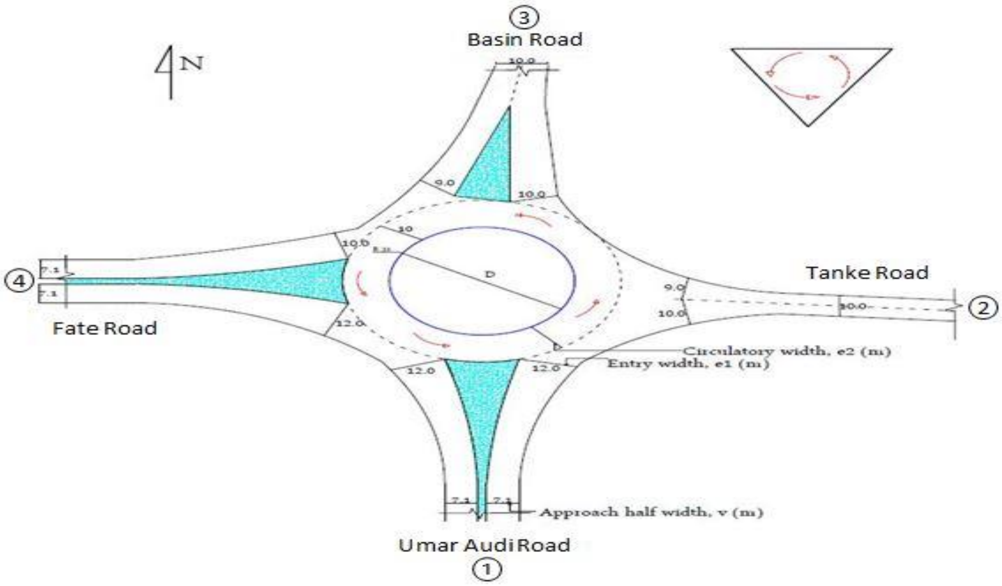



Figure 1: Map of Fate area showing Fate roundabout (Source: Nokia HERE Maps, 2015)




*Note: All dimensions in meters.*

Figure 2: Geometric parameters of Fate Roundabout

The capacity and performance analysis were then evaluated with the analytical (gap-acceptance) method described by the HCM. (2010).

## 3.0 Results and Discussions

### *3.1 Volumes on Each of the Approaches*

Results of Table 2 show that the heavy vehicle proportion (0) was less than 5%, indicating that the proportion of heavy vehicles had no effect on the capacity of the roundabout during the analysis period. This confirmed that heavy vehicles composition has no significant effect on the roundabout performance. Hence, the heavy vehicle adjustment factor, $f_{HV}$ was taken as unity, and the demand flow rate in veh/h was equal to the demand flow rate in pc/h.

It was observed from the traffic data collected that the peak period occurred between 7:30 to 8:30 am on all of the days, hence the reason foe selecting the hour of 7.30-8.30 for the study. Tables 2 presents the information on the movement of vehicles on Approach 1 (Basin Road) and Day 1 (Monday, 15th June, 2015). This represents sample calculations for the other study approaches and days.

Table 2: Movement of vehicles on Approach 1 (Day 1- peak period)

| Time | *Left Turns (LT)* | | | | *Through Turns (TT)* | | | | *Right Turns (RT)* | | | | *Total* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *Car* | *Bus* | *Truck* | *Bike* | *Car* | *Bus* | *Truck* | *Bike* | *Car* | *Bus* | *Truck* | *Bike* | |
| 7:30-7:45 | 53 | | | 11 | 50 | | | 9 | 25 | | | 5 | 153 |
| 7.45-8.00 | 49 | 1 | | 15 | 40 | | | 10 | 17 | 1 | | 11 | 144 |
| 8.00-8.15 | 41 | 1 | | 10 | 47 | | | 7 | 15 | | | 6 | 127 |
| 8.15-8.30 | 36 | | | 22 | 52 | | | 11 | 20 | | | 18 | 159 |
| TOTAL | 179 | 2 | 0 | 58 | 189 | 0 | 0 | 37 | 77 | 1 | 0 | 40 | 583 |
| Adjusted | 224 | 3 | 0 | 73 | 236 | 0 | 0 | 46 | 96 | 1 | 0 | 50 | 729 |

The raw volume counts were adjusted with a factor of 1.25 to make up for the time of recording, which was assumed to be 3 minutes out of every 15 minutes specified by HCM (2010) for counting. Hence, the raw volume counts were multiplied by 1.25 to give an adjusted volume (Peak periods).

### *3.2 Capacity and Performance Analysis Computation*

The results of traffic movements show that the Fate roundabout is mostly busy on working days. Therefore, the results of the five working days were used for the analysis. The capacity and performance analysis computation were carried out using the analytical method. The peak hour factors (PHFs) were estimated from the expression in Equation (4) (Rodegerdts *et al*., 2014) and the results presented in Table 3.

$$PHF = \frac{P_h}{4P_{15}} \tag{4}$$

where, PHF = peak hour factor, $P_h$ = Vehicle volume during peak hour, and $P_{15}$ = Vehicle volume during 15 minutes period of the one-hour analysis period. The PHF ranges from 0.833 – 0.966 for all the approaches on the roundabout as shown in Table 3, which indicates that there is approximately uniform demand on the roundabout.

Equation (5) (Rodegerdts *et al*., 2014) was used in converting the demand volumes from the traffic counts to the demand flow rates.

$$v_i = \frac{V_i}{PHF} \tag{5}$$

where, $v_i$ = demand flow rate (veh/h), $V_i$ = Demand volume (veh/h).

The demand volumes are the adjusted values of vehicle movements from the approaches into the roundabout (Table 2). For instance, the demand volume for approach 1 on Day 1 during peak period is 729 veh/h. The key performance indicators used for evaluating the performance analysis of the Fate Roundabout were; entry capacity, v/c ratio (degree of saturation), average delay and LOS. High pedestrian volume has a significant effect on capacity of a Roundabout. Although, there are no designated pedestrian crossings on the Fate Roundabout, counts showed that there were low (less than 50 pedestrians/hour) crossing during the counting exercise, which had no significant effects on the capacity of the roundabout.

Table 3: Peak Hour Factors

| *Day* | *Approach* | $P_{15}$ | *Peak Period PHF* |
|---|---|---|---|
| 1 | 1 | 8:15-8:30 | 0.917 |
| | 2 | 7.30-7.45 | 0.875 |
| | 3 | 7.45-8.00 | 0.907 |
| | 4 | 7.30-7.45 | 0.876 |
| 2 | 1 | 7:30-7:45 | 0.875 |
| | 2 | 7.30-7.45 | 0.868 |
| | 3 | 7.30-7.45 | 0.852 |
| | 4 | 7.30-7.45 | 0.833 |
| 3 | 1 | 7:30-7:45 | 0.895 |
| | 2 | 7.45-8.00 | 0.858 |
| | 3 | 8.15-8.30 | 0.925 |
| | 4 | 7.45-8.00 | 0.966 |
| 4 | 1 | 8:15-8:30 | 0.897 |
| | 2 | 7.45-8.00 | 0.957 |
| | 3 | 7.45-8.00 | 0.939 |
| | 4 | 8.00-8.15 | 0.853 |
| 5 | 1 | 8:30-8:45 | 0.859 |
| | 2 | 7.30-7.45 | 0.906 |
| | 3 | 11.00-11.15 | 0.871 |
| | 4 | 7.30-7.45 | 0.957 |

The heavy vehicle proportion were < 5%, indicating that the proportion of heavy vehicles had no effect on the capacity of the roundabout during the analysis period, and thus, has no significant effect on roundabout performance (Serhan *et al*., 2013). The summarized results for the circulatory flow rates ($q_c$), entry lane capacities ($C_e$), degree of saturation ($x_i$), average control delay ($d$), 95$^{th}$ percentile queues (Q95), and LOS for the peak periods are presented in Tables 4.

Results from Table 4 shows that the circulatory flow rates for all the approaches are in the range of 703-1082 pc/h during the peak period. The corresponding entry capacities are in the range of 1030-1487 pc/h. This shows the impact of circulating flow on entry capacity and their significance indices for performance evaluation of a roundabout. Also, the v/c ratios of all the approaches, except approaches 3 and 4 with values of

0.899 and 1.024, respectively on day 2, are higher than the threshold value of 0.85. This implies that approaches 3 and 4 experienced delay and queues leading to breakdown of services on day 2.

In addition, the average delays experienced during the peak period on the Fate roundabout ranges from 5 - 102 seconds for all approaches. The highest delay of 102 seconds was witnessed on approach 4 on day 2, while the lowest delay of 5 seconds was witnessed on approach 4 on day 5. This can be justified with the control delay of the entire roundabout shown in Table 5, where the highest average delay time of 45 seconds and the lowest value of 6 seconds were experienced on the roundabout on days 2 and 5 of the period of analysis, respectively. Approaches 3 and 4 operated on LOS D and F, respectively on day 2 during peak period. However, all the other approaches operated on LOS A-C on all other days as shown in Table 4. This further confirms the delay and queues experienced on approach 3 and 4 on day 2 of the analysis period.

Table 4: Summarized Results (Peak Period)

| *DAY* | *APPROACH* | $q_c$ *(pc/h)* | $C_e$ *(pc/h)* | $x_i$ | *d (s/veh)* | $Q_{95}$ *(Veh)* | *LOS* |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 841 | 1227 | 0.647 | 9 | 5 | A |
| | 2 | 934 | 1147 | 0.704 | 11 | 7 | B |
| | 3 | 874 | 1198 | 0.785 | 15 | 10 | B |
| | 4 | 829 | 1238 | 0.777 | 14 | 10 | B |
| 2 | 1 | 1075 | 1036 | 0.812 | 18 | 11 | C |
| | 2 | 1082 | 1030 | 0.783 | 16 | 10 | C |
| | 3 | 868 | 1204 | 1.024 | 26 | 19 | D |
| | 4 | 946 | 1137 | 0.693 | 102 | 42 | F |
| 3 | 1 | 778 | 1285 | 0.693 | 10 | 6 | A |
| | 2 | 961 | 1125 | 0.771 | 14 | 10 | B |
| | 3 | 946 | 1136 | 0.849 | 21 | 15 | C |
| | 4 | 886 | 1188 | 0.678 | 10 | 6 | A |
| 4 | 1 | 708 | 1352 | 0.598 | 7 | 5 | A |
| | 2 | 851 | 1218 | 0.626 | 8 | 7 | A |
| | 3 | 851 | 1218 | 0.689 | 10 | 7 | A |
| | 4 | 783 | 1279 | 0.692 | 10 | 3 | A |
| 5 | 1 | 576 | 1487 | 0.498 | 5 | 3 | A |
| | 2 | 703 | 1356 | 0.567 | 7 | 5 | A |
| | 3 | 812 | 1253 | 0.628 | 7 | 5 | A |
| | 4 | 735 | 1325 | 0.487 | 5 | 3 | A |

where,
Flow rate, $q_c$ is the sum of the left, right and through movements from each approach (Table 2) into the roundabout. Entry lane capacity was calculated using Equation (1). Degree of saturation is the ratio of the demand volume at the roundabout entry to the capacity of the entry. It is expressed as (HCM, 2010);

$$x_i = \frac{v_i}{c_i} \tag{6}$$

where, $x_i$= volume to capacity ratio at entry of subject lane i, $v_i$ = demand flow rate of subject lane, i (veh/h) and $c_i$ = capacity of the subject lane, i (veh/h).

Average delay is estimated from;

$$d = \frac{3600}{c_i} + 900T\left[ x_i - 1 + \sqrt{(x_i - 1)^2 + \frac{\left(\frac{3600}{c_i}\right)x_i}{450T}} \right] + 5 \tag{7}$$

where, d = average delay (mins), $x_i$= volume to capacity ratio at entry of subject lane i, $c_i$ = capacity of the subject lane, i (veh/h) and T = time period (h) (T = 0.25 h for a 15-min analysis.

$$Q_{95} = \left[ x_i - 1 + \sqrt{(x_i - 1)^2 + \frac{\left(\frac{3600}{c_i}\right)x_i}{450T}} \right] \tag{8}$$

### *3.3 Delay Determination*

The entire roundabout delay is the weighted average of the delay for each approach weighted by the volume on each approach and is given by the expression in Equation (9) (Douglas *et al.*, 2005) and the results presented in Table 5.

$$d_{intersection} = \frac{\sum d_i v_i}{\sum v_i} \tag{9}$$

where, $d_i$ = average control delay for lane $i$ (s/veh), $v_i$ = demand flow rate for subject lane i (veh/h)

Table 5: Control Delay of the entire roundabout

| *DAY* | *Control Delay (s/veh)* | |
|---|---|---|
| | *Peak Period* | *Off-peak period* |
| 1 | 12 | 4 |
| 2 | 45 | 4 |
| 3 | 14 | 4 |
| 4 | 9 | 4 |
| 5 | 6 | 3 |

### *3.4 Determination of Degree of Saturation (v/c Ratio)*

The average values of degree of saturation and LOS for the entire roundabout were computed using values from Table 5 and the results are presented in Table 6.

Table 6: Degree of Saturation and LOS for Entire Roundabout

| *Day* | *Degree of Saturation* | *LOS* |
|---|---|---|
| 1 | 0.728 | B |
| 2 | 0.880 | E |
| 3 | 0.748 | B |
| 4 | 0.652 | A |
| 5 | 0.545 | A |

Figure 3 shows the plot of Degree of Saturation to demonstrate the LOS of each of the approaches at the roundabout as against the maximum acceptable value of 0.85.

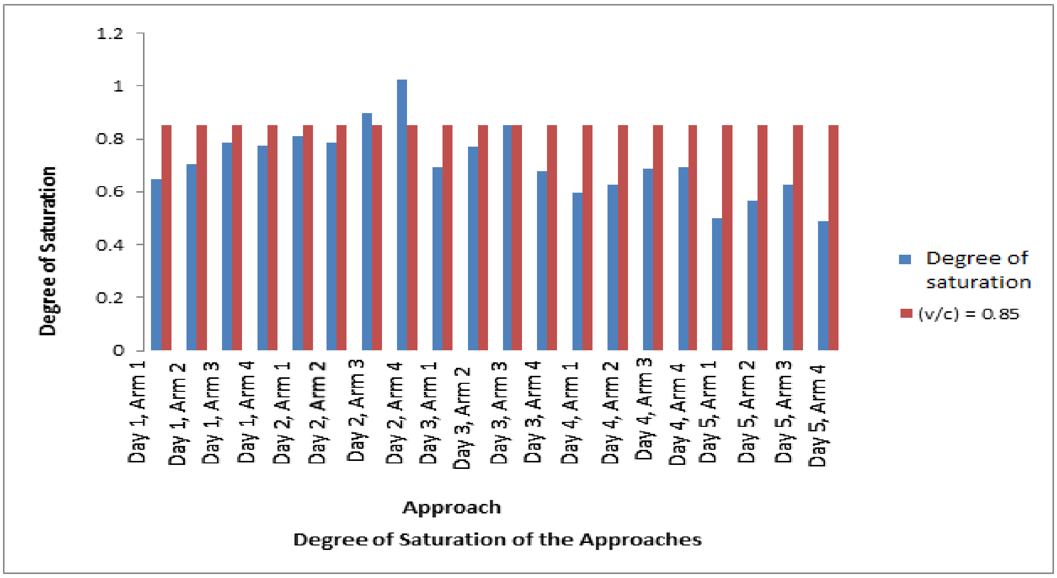



Figure 3: Degree of Saturation for Fate Roundabout (peak period)

A linear relationship developed between degree of saturation and entry flow rates for the roundabout gave a fairly high correlation with $R^2$ value of 0.820 as shown in Figure 4, which was further confirmed by results of Table 7.

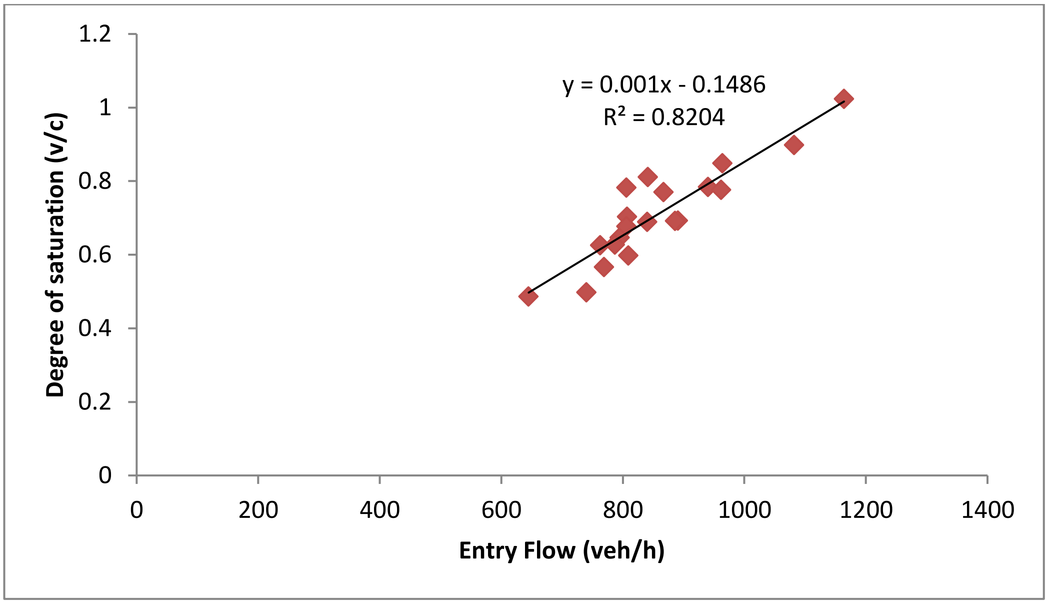



Figure 4: Entry Flow vs. Degree of Saturation for the Fate Roundabout

The results of Table 7 also indicated that approaches 3 and 4 on day 2 have v/c values exceeding the threshold value 0.85, and are thus in critical conditions. The relationships or the influences were observed from the capacity-circulatory flow curve shown in Figure 5, which further confirms the strong linear relationship between the capacities at the legs of the roundabout and the opposing circulatory flows with $R^2$ value of 0.996.

Table 7: Summarized capacity analysis results on the approach or legs (Peak Period)

| *DAY* | *APPROACH* | *$v_i$ (pc/h)* | *$q_c$ (pc/h)* | *(v/c ratio)* | *$C_e$ (pc/h)* | *v/c ratio - 0.85* |
|---|---|---|---|---|---|---|
| 1 | 1 | 795 | 841 | 0.647 | 1227 | -0.203 |
| | 2 | 807 | 934 | 0.704 | 1147 | -0.146 |
| | 3 | 940 | 874 | 0.785 | 1198 | -0.065 |
| | 4 | 962 | 829 | 0.777 | 1238 | -0.073 |
| 2 | 1 | 841 | 1075 | 0.812 | 1036 | -0.038 |
| | 2 | 806 | 1082 | 0.783 | 1030 | -0.067 |
| | 3 | 1082 | 868 | 0.899 | 1204 | +0.049 |
| | 4 | 1164 | 946 | 1.024 | 1137 | +0.174 |
| 3 | 1 | 891 | 778 | 0.693 | 1285 | -0.157 |
| | 2 | 867 | 961 | 0.771 | 1125 | -0.079 |
| | 3 | 964 | 946 | 0.849 | 1136 | -0.001 |
| | 4 | 806 | 886 | 0.678 | 1188 | -0.172 |
| 4 | 1 | 809 | 708 | 0.598 | 1352 | -0.252 |
| | 2 | 763 | 851 | 0.626 | 1218 | -0.224 |
| | 3 | 840 | 783 | 0.690 | 1218 | -0.160 |
| | 4 | 886 | 576 | 0.692 | 1279 | -0.158 |
| 5 | 1 | 740 | 576 | 0.498 | 1487 | -0.352 |
| | 2 | 769 | 703 | 0.567 | 1356 | -0.283 |
| | 3 | 787 | 812 | 0.628 | 1253 | -0.222 |
| | 4 | 645 | 735 | 0.487 | 1325 | -0.363 |

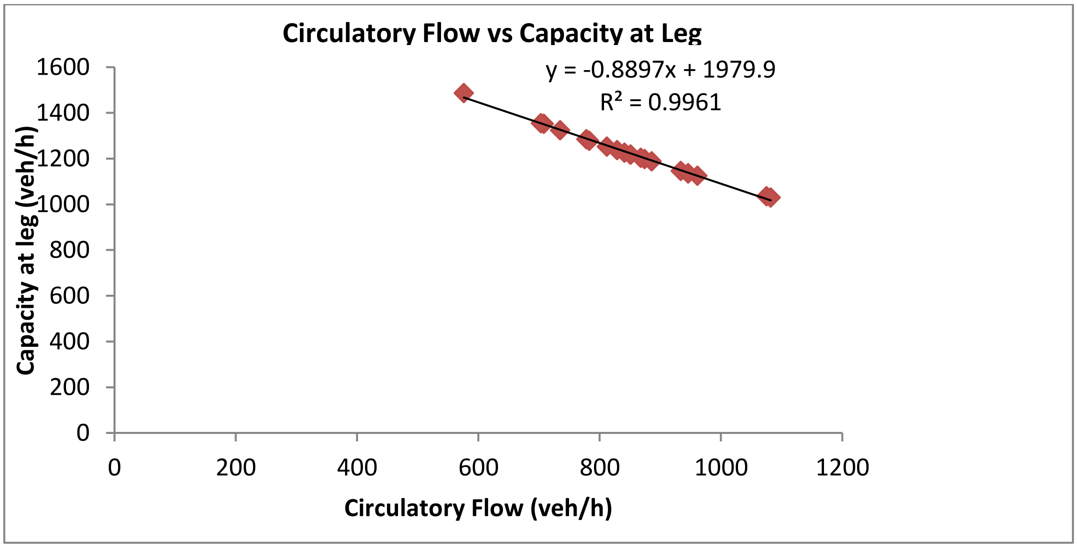



Figure 5: Opposing Circulatory Flows versus Capacity at Legs

## 4.0 Conclusions and Recommendations

### *4.1 Conclusions*

The following conclusions were drawn from the outcome of the study:

(i) The peak and off-peak periods occurred on all days on the Fate Roundabout between 7:30 – 8:30 am and 12:00 – 1:00 pm, respectively. Also, the pedestrian count is less than 50/hour, and, therefore has no significant effect on the roundabout capacity.
(ii) The average delays experienced during peak and off-peak periods ranges between 5 – 102 seconds and 3 – 5 seconds, respectively. Approach 4 experienced the highest delay of 102 seconds on day 2, while approach 5 witnessed the lowest delay of 5 seconds on day 5 of the analysis period.
(iii) The volume/capacity ratio of all the approaches, except approaches 3 and 4, with v/c ratios of 0.899 and 1.024, respectively on day 2, are lower than the threshold value of 0.85. This implies that approaches 3 and 4 witnessed delays and queues on day 2 of the analysis period.
(iv) Approach 4 operated on LOS F and approach 3 on LOS D, during the peak period of day 2. Other approaches operated on LOS A-C. This further confirms the delay and queues experienced on approaches 3 and 4.
(v) A strong linear relationship of the form $y = mx + c$ between capacities and circulatory flows on all legs was established with $R^2$ value of 0.996.
(vi) Approach 4 is the critical and only leg performing under capacity at the Fate Roundabout

### *4.2 Recommendations*

The following recommendations are made:

(i) Deflection and island splitters be introduced on leg 2 (Fate-Tanke Road) to make drivers reduce speeds and avoid collision between neighboring leg entering vehicles.
(ii) Marked pedestrian crossing should be introduced at the roundabout to guide pedestrians from accessing the central island in order to increase safety.
(iii) The entry width of approach 3, which is the most trafficked, be increased by at least 1 m to maintain continuous and smooth operations.
(iv) The geometric parameters of Fate Roundabout and other roundabouts should be obtained and made available to enhance comparison between the analytical and empirical method of capacity estimations, as more roundabouts are built with increasing vehicular traffic.

## 5.0 Acknowledgements

This paper cannot be put together without the tremendous background information made available by various research workers, authors of excellent books and articles, which have been referred to and listed in my references. I thank them.

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