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Research Paper

PERFORMANCE AND CAPACITY ANALYSIS OF BEKWAI ROUNDABOUT ON THE NEW BEKWAI ROAD, KUMASI-GHANA USING MICRO SIMULATION MODEL

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Roundabouts are an increasingly popular alternative to traffic signals for intersection control in the United States. Roundabouts have a number of advantages over traffic signals depending on the conditions. They reduce the severity of crashes since head-on and right-angle conflicts are nearly eliminated. They reduce through traffic speeds to provide a "calmer" roadway environment. They may consume less land area since turn pocket lanes are not needed and also have lower energy and maintenance costs. This study analyzed performance and capacity of Bekwai roundabout in Kumasi, Ghana using micro simulation model. Traffic and geometric data were collected on the field. The analysis revealed that Bekwai roundabout was operating at a level of service F, which represented worst conditions. Signalized intersection with 4 approach lanes was proposed to control all the movements. Exclusive pedestrian phases were proposed to protect pedestrians.

Keywords: Performance Analysis, Bekwai roundabout, Capacity analysis, Synchro/SimTraffic

INTRODUCTION

Modern roundabouts are circular intersections with specific traffic control and design features as defined by the Federal Highway Administration (FHWA, 2000). These features include yield control at entry, channelized approaches, and geometric approach curvature (deflection) to induce entering traffic to slow down to the design speed of the circulatory roadway. Roundabouts have characteristics that differentiate them from traffic circles, rotaries and traffic calming circles. Roundabouts have a proven safety record that is superior to other forms of traffic control (Oursten and Bared, 1995, Insurance Institute for Highway Safety, 2000, Schoon and van Minnen, 1994).

The New Bekwai Road is a principal arterial that runs in a North-East/South/West direction. The road covers an urban (study) length of

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about 4 km, (from the Gee-KATH Roundabout to Hotel Rexmar in Santasi). The road is mostly a single carriageway, about 85%, (from Gee Roundabout to Santasi roundabout – 3.4 km). The road is paved throughout its entire length. The New Bekwai Road provides a major link between the Western By-Pass/Southern By-Pass to the Bantama High Street/Bantama Road. The major intersections are the KATH Roundabout, Bekwai Roundabout, Santasi Roundabout and the Cedar Avenue intersection (BCEOM and ACON Report, 2004).

Bekwai roundabout gets very congested causing major delays to motorists. This is partly due to the volume of traffic entering these intersections, which have inadequate capacities as well as driver indiscipline. This creates congestion and consequent delay at the intersection. The section of the road between Gee Roundabout and Bekwai Roundabout is normally congested due to the inefficient control at the two (2) nodes (BCEOM and ACON Report, 2004). It can be observed that the worst sections on the New Bekwai Road are between Gee roundabout and Bekwai Roundabout and between Bekwai Roundabout and Cedar Avenue intersection. This is largely due to the type of controls at the intersections, which are unsignalised. It can also be attributed to critical/inadequate capacities and abuse by motorists and/or pedestrian. The sidewalks are in bad condition. The crosswalk on this section is very busy but it is uncontrolled. The section between Bekwai Roundabout and Santasi Roundabout has sidewalks but they are also in bad condition. The newly constructed dual carriageway section from the Santasi Roundabout southwards has well defined sidewalks and crosswalks (BCEOM and ACON Report, 2004).

Previous studies on the performance of the roundabout attributed the congestion critical capacity and abuse to motorists and/or pedestrians. As part of the recommendations, the report proposed to improve upon the signalization and capacity at Bekwai roundabout. They recommended that if at-grade capacity cannot be obtained for the minimum requirements, then a grade separation scheme should be constructed at the roundabout. This could either be a flyover or an interchange (BCEOM and ACON Report, 2004).

These recommendations have not been implemented due to lack of funds and therefore long queues and frequent delays still persist during peak hour conditions at the roundabout. It is in this light that this study was undertaken to analyze once again the performance and capacity of Bekwai roundabout in Kumasi to find out possible, cheaper and effective way of resolving the traffic congestion problem in the interim or short term basis.

METHODOLOGY

Site Selection and Description

Bekwai roundabout was selected based on the levels of congestion associated with the roundabout. It is a 4-legged roundabout as shown in Figure 1. It is one of the major intersections on the New Bekwai road. It has four (4) legs, comprising:

- Kejetia leg - one (1) approach/entry and exit lanes

Figure 1: Geometry of Bekwai Roundabout

- Sofoline Roundabout leg - one (1) approach/ entry and exit lanes.
- Santasi Roundabout leg - one (1) approach/ entry and exit lanes
- City Hotel leg - one (1) approach/entry and exit lanes.

Basic Theoretical Background

One of the oldest and most well known cases of the use of simulation in theoretical research is the "car-following" analysis based on the Generalized General Motors (GM) models. In these models a differential equation governs the movement of each vehicle in the platoon under analysis (Gerlough and Huber, 1975). Car-following, like the intersection analysis, is one of the basic equations of traffic flow theory and simulation, and the analysis has been active after almost 40 years from the first trials (McDonald *et al.*, 1998). The car-following theory is of significance in microscopic traffic flow theory and has been widely applied in traffic safety analysis and traffic simulation (Luo *et al.*, 2010; Tordeux *et al.*, 2010). There have been many car-following models in the past 60 years, and the models can be divided into two categories. One is developed from the viewpoint of traffic engineering and the other is based on statistical physics. From the perspective of traffic engineers (Brackstone and McDonald, 1999), car-following models can be classified as stimulus-response models (Gazis *et al.*, 1961; Newell, 1961), safety distance models (Gipps, 1981), psycho-physical models (Wiedemann, 1974), and artificial intelligence models (Kikuchi and Chakroborty, 1992; Wu *et al.*, 2000).

The car-following theory is based on a key assumption that vehicles will travel in the center line of a lane, which is unrealistic, especially in developing countries. In these countries, poor road conditions, irregular driving discipline, unclear road markings, and different lane widths typically lead to non-lane-based car-following driving (Gunay, 2007). Heterogeneous traffic, characterized by diverse vehicles, changing composition, lack of lane discipline, etc., results in a very complex behavior and a non-lane-based driving in most Asian countries (Mathew and Radhakrishnan, 2010). Therefore, it is difficult for every vehicle to be moving in the middle of the lane. Vehicles are positioned laterally within their lanes, and the off central-line effect results in lateral separations. However, to the limit of our knowledge, the effect of lateral separation in the car-following process has been ignored by the vast majority of models. A few researchers have contributed efforts on this matter. Gunay (2007) first developed a car-following model with lateral discomfort. He improved a stopping distance based approach that was proposed by (Gipps, 1981), and presented a new car-following model, taking into account lateral friction between vehicles.

Jin *et al.* (2010) proposed a non-lane-based car following model using a modified full-velocity difference model. All the above models have assumed that drivers are able to perceive distances, speeds, and accelerations. However, car-following behavior is a human process. It is difficult for a driver of the following vehicle to perceive minor lateral separation distances, and drivers may not have precise perception of speeds and distances, not to mention accelerations.

Car-Following Models

The logic used to determine when and how much a car accelerates or decelerates is crucial to the accuracy of a microscopic simulation model. Most simulation models use variations on the GM model. Although it was developed in the 1950s and 1960s, it has remained the industry standard for describing car-following behavior and continues to be verified by empirical data. A variation on the GM model is the PITT car-following model, which is utilized in FRESIM. The GM family of models is perceived to be the most commonly used in microscopic traffic simulation models and are, therefore, the focus of this article.

Generalized General Motors Models

The first GM model modeled car-following is a stimulus-response process in which the following vehicle attempts to maintain space headway. When the speed of a leading vehicle decreases relative to the following vehicle, the following vehicle reacts by decelerating. Conversely, the following vehicle accelerates when the relative speed of the leading vehicle increases. This process can be represented by the first GM model, given Equation (1).

$$\ddot{\chi}_F = \alpha_F \times \left(\dot{\chi}_L(t) - \dot{\chi}_F(t) \right) \quad ...(1)$$

where: $\ddot{\chi}_F$ = Acceleration of the following vehicle,

$\dot{\chi}_F$ = Speed of the following vehicle,

$\dot{\chi}_L$ = Speed of the leading vehicle,

α_F = Sensitivity of the following vehicle, and t = time.

PITT Car-Following Model

FRESIM uses the PITT car-following model, which is expressed in terms of desired space headway, shown in the Equation (2).

$$h_s(t) = L + m + kV_2 + bk[V_1(t) - V_2(T)]^2 \quad ...(2)$$

where

$hs(t)$ = Desired space headway at time t,

L = Length of leading vehicle,

m = Minimum car-following distance (PITT constant),

k = Car-following sensitivity factor for following vehicle,

b = Relative sensitivity constant,

$v_1(t)$ = Speed of leading vehicle at time t, and

$v_2(t)$ = Speed of following vehicle at time t.

Equation above can be solved for the following vehicle's acceleration, given by the equation 3.

$$a = \frac{2 \times \left\lfloor x - y - L - m - V_2(K + T) - bk(V_1(t) - V_2(t))^2 \right\rfloor}{T^2 + 2KT} \quad ...(3)$$

where a = The acceleration of the following vehicle,

T = The duration of the scanning interval,

x = Position of the leading vehicle, and

y = Position of the following vehicle.

Algorithm on Synchro/SimTraffic software

Simulation is basically a dynamic representation of some part of the real world achieved by building a computer model and moving it through time. The results obtained from any simulation model will be as good as the model replicates the specific real world characteristics of interest to the analyst.

Once a vehicle is assigned performance and driver characteristics, its movement through the network is determined by three primary algorithms:

Car Following

This algorithm determines behavior and distribution of vehicles in traffic stream. Synchro varies headway with driver type, speed and link geometry whereas SimTraffic generates lower saturation flow rates.

Lane Changing

This is always one of the most temperamental features of simulation models. There are three types of lane-changing which includes

- Mandatory lane changes (e.g., a lane is obstructed or ends)
- Discretionary lane changes (e.g., passing)
- Positioning lane changes (e.g., putting themselves in the correct lane in order to make a turn): There is heavy queuing and this is a common problem for modeling positioning lane changes. Vehicles often passed back of queue before attempting lane change and their accuracy relates to degree of saturation and number of access points such as congested conditions which requires farther look ahead and densely-spaced access (i.e., short segments) which presents a problem.

Gap Acceptance

Gap acceptance affects driver behavior at unsignalized intersections, driveways (e.g., right-in-right-out) and Right-Turn-on-Red (RTOR) movements. If default parameters are too aggressive, vehicle delay will be under-estimated and there is serious implication for frontage roads. Conversely, parameters which are too conservative may indicate need for a signal when one isn't necessary. Gap acceptance parameters are network-wide in SimTraffic.

Turning Movement Counts

Data was collected manually at Bekwai roundabout because it was difficult getting good elevation observer positions. Turning movement counts were collected between 0600 h and 1800 h during the morning and evening peak periods of the day at the roundabout. Two enumerators each were positioned on each leg of the approach to the roundabout. The number of vehicles entering and leaving any of the four principal arterials such as Sofoline roundabout, City Hotel, Santasi roundabout and Kejetia were counted using the vehicle number plate method. All the Turning movement counts were conducted at 15 min intervals.

Intersection Capacity Analysis for Bekwai Roundabout

The Department of Transport of the UK recommends a research carried out by the Transport and Road Research Laboratory (TRRL) that predicts an equation for the determination of the capacities of roundabouts. The predictive equation for entry capacity into the circulatory area was used for entry capacity determination and is given by Equation (4).

$$Qe = K^*(F - f_c\,Qc) \quad \text{... (4)}$$

where

Qe is the entry flow into the circulatory area in passenger car units per hour (pcu/h)

Qc is the flow in the circulatory area in conflict with the entry flow in passenger car units per hour (pcu/h).

$K = 1\text{-}0.00347(f - 30) – 0.978(1/r – 0.05)$

$F = 303X_2$

$f_c = 0.21tD(1+0.2X_2)$

$tD = 1+0.5/(1+M)$

$M = \exp[(D – 60)/10]$

$X_2 = v + (e – v)/(1+2S)$

$S = 1.6(e- – v)/l¢$

e = Entry width (meters) - measured from a point normal to the rear kerbside

v = Approach half-width: measured along a normal from a point in the approach stream from any entry flare

l' = Average effective flare length: measured along a line drawn at right angles from the widest point of the entry flare

S = Sharpness of flare: indicates the rate at which extra width is developed within the entry flare

D = Inscribed circle diameter: the biggest circle that can be inscribed within the junction

ϕ = Entry angle: measures the conflict angle between entering and circulating traffic

r = Entry radius: indicates the radius of curvature of the nearside kerb line on entry.

Intersection Capacity Analysis

The intersection Capacity analysis was performed using Intersection Capacity Utilization (ICU) to determine the Level of Service (LOS) at Bekwai roundabout. An initial analysis was performed for the existing rotary intersection to determine its performance. Once the ICU was fully calculated, the ICU LOS for the roundabout was subsequently calculated based on the criteria given by Husch, 2010 in Table 1.

RESULTS AND DISCUSSION

Turning Movement Counts

Summary of total approach volume for each approach at Bekwai roundabout is shown in Table 2.

From Table 2, it was realized that East Bound Through (EBT), V_2 had the highest hourly flow rate of 938 veh/h at Bekwai roundabout. This

Table 1: Intersection Capacity Utilization LOS and Grading Criteria

LOS	ICU (%)	Grading Criteria
A	≤55	Intersection has no congestion
B	55<ICU<64	Intersection has very little congestion
C	64<ICU<73	Intersection has no major congestion
D	73<ICU<82	Intersection normally has no congestion
E	82<ICU<91	Intersection is on the verge of congested conditions
F	91<ICU<100	Intersection is over capacity and likely experiences congestion periods of 15 to 60 consecutive minutes
G	1005<ICU<109	Intersection is 9% over capacity and experiences congestion periods of 60 to 120 consecutive minutes.
H	>109%	The intersection is 9% or greater over capacity and could experience congestion periods of over 120 minutes per day.

Table 2: Summary of Total Approach volume at Bekwai Roundabout

Approaches	Hourly flow rate (veh/hr)
East Bound Left (EBL), V_1	268
East Bound Through (EBT), V_2	938
East Bound Right (EBR), V_3	549
West Bound Left (WBL), V_4	154
West Bound Through (WBT), V_5	726
West Bound Right (WBR), V_6	600
North Bound Left (NBL), V_7	469
North Bound South East (WBT), V_8	831
North Bound Right (NBR), V_9	214
South Bound Left (SBL), V_{10}	603
South Bound Through (SBT), V_{11}	616
South Bound Right (SBR), V_{12}	722

meant that 938 vehicles traversed the East Bound through direction in an hour. Similarly, West Bound Left (WBL), V_4 had the lowest hourly flow rate of 154 veh/h meaning 154 vehicles traversed the West Bound left direction within an hour.

Table 3: Approach Flow at Bekwai Roundabout

Approach Flow (veh/hr)	Approach Volume, Va
$Va,E = V_1+V_2+V_3$	1756
$Va,W = V_4+V_5+V_6$	1481
$Va,N = V_7+V_8+V_9$	1514
$Va,S = V_{10}+V_{11}+V_{12}$	1942

From Table 3 above, Santasi roundabout approach (Va, S) had the highest approach flow of 1942 veh/h at Bekwai roundabout. 1756veh/hr came from City Hotel approach (Va, E), followed by Kejetia approach (Va, N) which had 1514 veh/h. Sofoline roundabout approach (Va,W) gave the lowest approach volume of 1481 veh/h.

From Table 4 above, Kejetia approach (Vc, N) had the highest circulating flow of 1809 veh/h at Bekwai roundabout, followed by Sofoline approach (Vc, W) which gave a circulating flow of 1568 veh/h. City Hotel approach (Vc, E) had a circulating flow of 1374 veh/h with Santasi roundabout approach (Vc, S) having the lowest circulation flow of 1349 veh/h. Similarly, in terms of flow in pcu, Kejetia roundabout (Vc, N) gave the highest flow of 1990 pcu/h and Santasi roundabout approach (Vc, S) gave the least flow of 1484 pcu/h.

Entry Capacity, Circulating Flow and Reserve Capacities for Each Approach at Bekwai Roundabout is shown in Table 5.

From Table 5, it was realized that the Kejetia approach had the highest circulatory flow of 2239 pcu/h at Bekwai roundabout. This meant that 2239 of the flow in the circulatory area was in conflict with the entry flow of 243. Santasi roundabout approach had the lowest circulatory flow of 1670 pcu/h. This again meant that 1670 of the flow in the circulatory area was in conflict with the entry flow of 1428.

The flow to capacity ratios of each approach at Bekwai Roundabout is shown in Table 6.

From Table above 6, it was realized from the capacity analysis that Bekwai roundabout was at full capacity based on the overall volume to capacity ratio. The above flow to capacity ratios revealed that Bekwai roundabout was operating at a level of service F. Level of

Table 4: Circulating flows at Bekwai Roundabout

Circulating Flow	Flow, Qc (veh/hr)	Flow in pcu/hr (x1.1)	Factored Flow (x1.125)
$Vc,E = V_4+V_{10}+V_{11}$	1374	1511	1700
$Vc,W = V_1+V_7+V_8$	1568	1725	1940
$Vc,N = V_1+V_2+V_{10}$	1809	1990	2239
$Vc,S = V_4+V_5+V_7$	1349	1484	1670

Table 5: Entry Capacity, Circulating Flow And Reserve Capacity For The Approaches At Bekwai Roundabout

Parameters	City Hotel	Sofoline	Kejetia	Santasi R/A
Entry width, e	6	6	6	6
Approach Half width, v	4	4	4	4
Average Effective Flare Length, l'	15	15	15	15
Sharpness of Flare, S	0.213333333	0.213333333	0.213333333	0.213333333
Inscribed Circle Diameter, D	42	42	42	42
Entry Angle, ϕ	30	30	30	30
Entry Radius, r	30	30	30	30
M	0.165298888	0.165298888	0.165298888	0.165298888
X_2	5.401869159	5.401869159	5.401869159	5.401869159
tD	1.429074468	1.429074468	1.429074468	1.429074468
fc	0.624331916	0.624331916	0.624331916	0.624331916
F	1636.766355	1636.766355	1636.766355	1636.766355
K	1.0163	1.0163	1.0163	1.0163
Qc	1700	1940	2239	1670
Qe	585	432	243	1428

Table 6: Flow to Capacity Ratios at Bekwai Roundabout

Approaches	Circulating Flow Qc	Entry Capacity (pcu/h)	Entry Flow (pcu/h)	Reserve Capacity (%)	Flow to capacity ratio
City Hotel	1700	585	1756	-200	3.0
Sofoline R/A	1940	432	1481	-243	3.4
Kejetia	2239	243	1514	-523	6.2
Santasi R/A	1670	1428	1942	-36	1.4

Table 7: Performance of Bekwai Roundabout

Intersection	Control Type	v/c ratio	ICU %	ICU LOS
Bekwai Roundabout	Roundabout	3.5	157.9	H

Table 8: Proposed Geometric Data for Bekwai Roundabout

Intersection: Bekwai Roundabout							
Movement	**From (Area)**	**To (Area)**	**Veh/h**	**% of Heavy Vehicles**	**No. of Lanes**	**Lane Width (m)**	**Storage Length (m)**
EBL	Sofoline R/A	Kejetia	514	3	1	3.0	120.0
EBT		City Hotel	616	11	2	3.3	
EBR		Santasi	496	7	1	3.0	120.0
WBL	City Hotel	Santasi	352	19	1	3.0	150.0
WBT		Sofoline R/A	597	8	2	3.3	
WBR		Kejetia	115	5	1	3.0	80.0
NEBL	Santasi	Sofoline R/A	448	9	1	3.0	150.0
NEBT		Kejetia	639	16	2	3.3	
NEBR		City Hotel	462	12	1	3.0	120.0
SWBL	Kejetia	City Hotel	210	4	1	3.3	
SWBT		Santasi	989	19	2	3.3	
SWBR		Sofoline R/A	417	4	1	3.0	120.0

service F described a forced-flow operation at low speeds, where volumes were below capacity. These conditions usually resulted from queues of vehicles backing up a restriction downstream at the roundabout. Speeds were reduced substantially and stoppages occurred for short or long periods of time because of the downstream congestion. It represented worst conditions.

Intersection Capacity Analysis

Performance of Bekwai roundabout after capacity analysis is shown in Table 7

From Table 7 above, the result showed that Bekwai roundabout was performing beyond capacity in that, the roundabout was 9% or greater over capacity and was experiencing congestion over 2 hours per day.

Signalization and Improvement at Bekwai Roundabout

The proposed Geometry for Bekwai Roundabout is shown in Figure 2.

Signalized intersection with 4 approach lanes was proposed as shown in Figure 2. The Bekwai roundabout signalization was basically to improve on vehicular movement. By critical and careful examination of the conditions, signalization of Bekwai roundabout was proposed to control all the movements. The proposed geometric data in Table 8 when implemented will improve upon the

Figure 2: Proposed Geometry for Bekwai Roundabout

performance of the intersection. The central island would be channelized to aid motorists to move from one approach to the other in order to prevent conflicts and enhance safety. Pedestrian movements would be separated in order not to interrupt the flow by considering the number of lanes at each approach to the roundabout. A pedestrian footbridge was thus proposed on all legs to the roundabout.

CONCLUSION

Bekwai roundabout was performing at full capacity based on the overall volume to capacity ratio. Bekwai roundabout should be signalized to control all the movements. It is cheaper to implement the signalized intersection to control and alleviate vehicular movement than implementing the interchange. The central island should be channelized to enable motorists move from one approach to the other in order to prevent conflicts and enhance safety. A pedestrian footbridge should be constructed on all legs to the roundabout.

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