PERFORMANCE EVALUATION OF SANTASI ROUNDABOUT, KUMASI-GHANA USING MICRO SIMULATION MODEL

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Abstract

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 evaluated performance of Santasi roundabout in Kumasi, Ghana using micro simulation model. Traffic and geometric data were collected on the field. The analysis revealed that Santasi 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.

***Index Terms**: Performance evaluation, Santasi roundabout, Capacity analysis, Transportation network performance*

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1. INTRODUCTION

As defined by the Federal Highway Administration [1], modern roundabouts are circular intersections with specific traffic control and design features. 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. The crosswalks are set back from the intersection to minimize conflicts with turning vehicles. 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 [2 - 4]. Santasi roundabout is one of the major intersections on the New Bekwai Road. The roundabout gets very congested causing major delays to motorists. This is partly due to the volume of traffic entering the intersection which has inadequate capacities as well as driver indiscipline [5]. The traffic from the Cedar Avenue feeding into the New Bekwai Road is quite heavy. This intersection is quite close to the Santasi Roundabout as such the approach is normally slow moving and heavy, which makes it difficult for vehicles from the Cedar Avenue to find gaps to move into. This creates congestion and consequent delay at the intersection [5].

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 Santasi 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 [5].

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 evaluate once again the performance of Santasi roundabout in Kumasi to find out possible, cheaper and effective way of resolving the traffic congestion problem in the interim or short term basis.

2. METHODOLOGY

2.1 Site Selection and Description

Santasi roundabout was selected based on its accident and safety records in the past and also the levels of congestion associated with the roundabout. Santasi roundabout is the intersection of three (3) Principal arterials, namely: New Bekwai Road, Western By-Pass and Southern By-Pass as shown in Fig.1

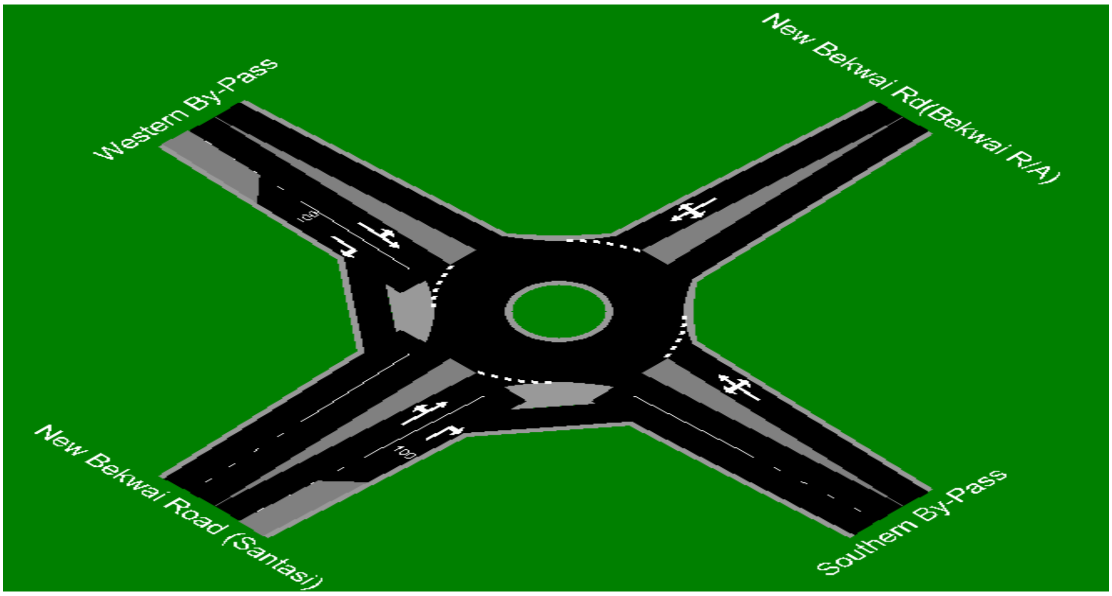

Fig-1: Geometry of Santasi Roundabout; Source: BCEOM and ACON Report (2004)

2.2 Study Area

2.2.1 New Bekwai Road

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 about 4 km, (from the Gee-KATH Roundabout to Hotel Rexmar in Santasi). The road is mostly a single carriageway, about 85 percent, (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 on the road are the KATH Roundabout, Bekwai Roundabout, Santasi Roundabout and the Cedar Avenue intersection. The roundabouts get 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. The traffic from the Cedar Avenue feeding into the New Bekwai Road is quite heavy. This intersection is quite close to the Santasi Roundabout as such the approach is normally slow moving and heavy, which makes it difficult for vehicles from the Cedar Avenue to find gaps to move into. 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. 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.

2.2.2 Western By-Pass

The Western By-Pass is a principal arterial that runs in an East/West direction, (Suame Roundabout to Sofoline Roundabout) and North/South direction, (Sofoline Roundabout to Santasi Roundabout). It covers a distance of about 5.3 km, (from Suame Roundabout to Santasi Roundabout). The road is paved for the entire length and comprises both single carriageway (about 63 percent), and two-lane dual carriageway (about 37 percent). The single carriage way is from Sofoline Roundabout to Santasi Roundabout (about 3.4 km), and the dual carriage way is from Suame Roundabout to Sofoline Roundabout, (about 1.9 km). The road forms part of the Ring road.

2.2.3 Southern By-Pass

The Southern By-Pass is an East-West principal arterial, covering a distance of about 4.2 km, (from the Lake road intersection to the Santasi Roundabout). The road is a single carriageway and it is paved throughout its entire length. The Southern By-Pass forms part of the Ring road and it provides a major link between two (2) principal arterials namely, the Western By-Pass and the Lake road.

A minimal level of congestion was observed on this road. The approaches to the intersections are the main areas that are congested during the peak periods. Long vehicles carrying timber logs ply this route regularly and because of their slow moving nature, they reduce the average travelling speed of other vehicles.

The Lake Road intersection is a major cause congestion on road. Vehicles queue for long before they are able to clear the unsignalised intersection. The Ahodwo Roundabout causes some amount of delay, but it is normally not too serious. The unsignalised Adiembra Road intersection becomes congested, especially during the peak periods. Pedestrians are guided to cross the road at the intersection by traffic wardens during the peak periods. The Santasi Roundabout is a congested area, which causes a lot of delay to motorist on the various approaches. A considerable length of vehicles queue on the approach from the Southern By-Pass during the peak periods.

2.3 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 [6]. 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 [7].The car-following theory is of significance in microscopic traffic flow theory and has been widely applied in traffic safety analysis and traffic simulation [8, 9]. 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 [10], car-following models can be classified as stimulus-response models [11,12], safety distance models [13], psycho-physical models [14], and artificial intelligence models [15, 16].

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 [17]. 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 [18]. 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. [17] first developed a car-following model with lateral discomfort. He improved a stopping distance based approach that was proposed by [13], and presented a new car-following model, taking into account lateral friction between vehicles. [19] 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.

2.3.1 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.

2.3.1.1 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.

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

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.

2.3.1.2 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.

$$h_s(t) = L + m + kV_2 + bk[V_1(t) - V_2(T)]^2 \qquad \text{Eq. (2)}$$

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,
v1 (t) = speed of leading vehicle at time *t*, and
v2 (t) = speed of following vehicle at time *t*.

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

$$a = \frac{2 \times \left[x - y - L - m - V_2(K + T) - bk(V_1(t) - V_2(t))^2\right]}{T^2 + 2KT} \qquad \text{Eq. (3)}$$

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.

2.4 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:

2.4.1 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.

2.4.2 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.

2.4.3 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 underestimated 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.

2.4.4 Turning Movement Counts

Data was collected manually at Santasi roundabout because it was difficult getting good elevation observer positions. Turning movement counts were collected between 0600hours and 1800 hours 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 three principal arterials such as New Bekwai, Southern By-Pass and the Western By-Pass road were counted using the vehicle number plate method. All the Turning movement counts were conducted at 15min intervals.

2.4.5 Intersection Capacity Analysis for Suame 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.

$$Qe = K^*(F - fc\ Qc) \qquad \text{Eq. (4)}$$

Where
Qe is the entry flow into the circulatory area in passenger car units per hour (pcu/hr)
Qc is the flow in the circulatory area in conflict with the entry flow in passenger car units per hour (pcu/hr).
$K = 1-0.00347(\phi - 30) - 0.978(1/r - 0.05)$
$F = 303X_2$
$fc = 0.21tD(1+0.2X_2)$
$tD = 1+0.5/(1+M)$
$M = \exp[(D - 60)/10]$
$X_2 = v + (e - v)/(1+2S)$
$S = 1.6(e - v)/l'$
e = entry width (metres) - 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.

2.4.6 Intersection Capacity Analysis

The intersection Capacity analysis was performed using intersection capacity utilization (ICU) to determine the Level of service (LOS) at Santasi 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 [20] Table -1.

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.

3. RESULTS AND DISCUSSION

3.1 Turning Movement Counts

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

Table -2: Summary of Total Approach volume at Santasi Roundabout

Approaches	Hourly flow rate (veh/hr)
East Bound Left (EBL), V_1	469
East Bound Through (EBT), V_2	968
East Bound Right (EBR), V_3	693
West Bound Left (WBL), V_4	268
West Bound Through (WBT), V_5	1206
West Bound Right (WBR), V_6	600
North Bound Left (NBL), V_7	281
North Bound South East (WBT), V_8	906
North Bound Right (NBR), V_9	145
South Bound Left (SBL), V_{10}	536
South Bound Through (SBT), V_{11}	884
South Bound Right (SBR), V_{12}	603

Source: from study

From Table 2, it was realized that West Bound Through (WBT), V5 had the highest hourly flow rate of 1206 veh/hr at Santasi roundabout. This meant that 1206 vehicles traversed the West Bound through direction in an hour. Similarly, North Bound Right (NBR), V9 had the lowest hourly flow rate of 145 veh/hr meaning 145 vehicles traversed the North Bound right direction within an hour.

Table - 3: Approach Flow at Santasi Roundabout

Approach Flow (veh/hr)	Approach Volume, Va
$Va,E = V_1+V_2+V_3$	2129
$Va,W = V_4+V_5+V_6$	2074
$Va,N = V_7+V_8+V_9$	1332
$Va,S = V_{10}+V_{11}+V_{12}$	2024

Source: from study

From Table 3 above, Ahodwo roundabout approach (Va, E) had the highest approach flow of 2129veh/hr at Santasi roundabout. 2074veh/hr came from Sofoline approach (Va,W), followed by Santasi approach (Va,S) which had 2024veh/hr. Bekwai roundabout approach (Va,N) gave the lowest approach volume of 1332 veh/hr.

Table -4: Circulating flows at Santasi Roundabout

Circulating Flow	Flow, Qc (veh/hr)	Flow in pcu/hr (x1.1)	Factored Flow (x1.125)
Vc,E = $V_4+V_{10}+V_{11}$	1689	1857	2090
Vc,W = $V_1+V_7+V_8$	1656	1822	2050
Vc,N = $V_1+V_2+V_{10}$	1973	2170	2441
Vc,S = $V_4+V_5+V_7$	1756	1931	2172

Source: from study

From Table 4 above, Bekwai roundabout approach (Vc,N) had the highest circulating flow of 1973veh/hr at Santasi roundabout, followed by Santasi approach (Vc,S) which gave a circulating flow of 1756veh/hr. Ahodwo roundabout approach (Vc,E) had a circulating flow of 1689veh/hr with Sofoline approach (Vc,W) having the lowest circulation flow of 1656veh/hr. Similarly, in terms of flow in pcu, Bekwai roundabout (Vc,N) gave the highest flow of 2170pcu/hr and Sofoline approach (Vc,W) gave the least flow of 1857pcu/hr.

Entry capacity, circulating flow and reserve capacities for each approach at Santasi roundabout is shown in Table 5.

Table -5: Entry capacity, circulating flow and reserve capacity for the approaches at Santasi Roundabout

Parameters	Ahodwo Roundabout	Sofoline	Bekwai Roundabout	Santasi
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	2090	2050	2441	2172
Qe	338	363	115	987

Source: from study

From Table 5, it was realized that the Bekwai roundabout approach had the highest circulatory flow of 2441pcu/hr at Santasi roundabout. This meant that 2441 of the flow in the circulatory area was in conflict with the entry flow of 115. Sofoline had the lowest circulatory flow of 20500pcu/hr. This again meant that 2050 of the flow in the circulatory area was in conflict with the entry flow of 363.

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

Table -6: Flow to Capacity ratios at Santasi Roundabout

Approaches	Circulating flow, Qc	Entry capacity (pcu/hr)	Entry flow (pcu/hr)	Reserve capacity (%)	Flow to capacity ratio
Ahodwo Roundabout	2090	338	2129	-531	6.3
Sofoline Roundabout	2050	363	2074	-472	5.7
Bekwai Roundabout	2441	115	1332	-1063	11.6
Santasi	2172	987	2024	-105	2.1

Source: from study

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

3.3 Intersection Capacity Analysis

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

Table 7: Performance of Santasi roundabout

Intersection	Control Type	v/c ratio	ICU %	ICU LOS
Santasi Roundabout	Roundabout	3.35	157.9	H

Source: from study

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

3.3 Signalization and Improvement at Santasi Roundabout

The proposed Geometry for Santasi Roundabout is shown in Fig.2.

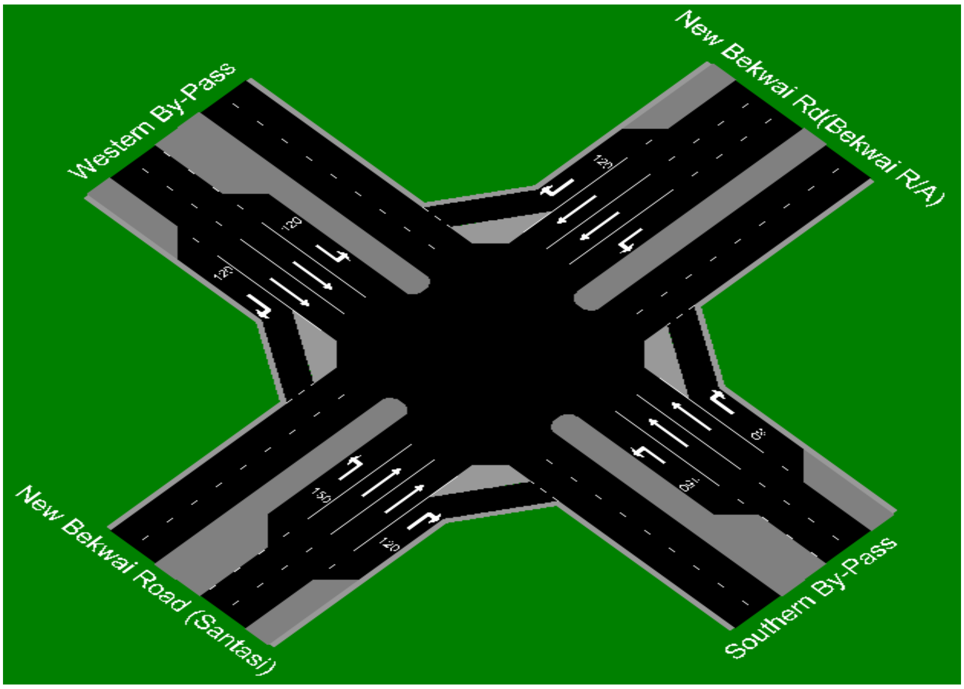

Figure 3: Proposed Geometry for Santasi Roundabout; Source: from study

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

Table -9: Proposed Geometric Data for Santasi Roundabout

Intersection: Santasi Roundabout							
Movement	From (Area)	To (Area)	Veh/hr	% of Heavy vehicles	No. of Lanes	Lane width (m)	Storage Length (m)
EBL		Bekwai R/A	534	5	1	3.0	120.0
EBT	Sofoline R/A	Ahodwo R/A	646	14	2	3.3	
EBR		Santasi	536	11	1	3.0	120.0
WBL		Santasi	393	28	1	3.0	150.0
WBT	Ahodwo R/A	Sofoline R/A	654	12	2	3.3	
WBR		Bekwai R/A	143	9	1	3.0	80.0
NEBL		Sofoline R/A	482	11	1	3.0	150.0
NEBT	Santasi	Bekwai R/A	689	25	2	3.3	
NEBR		Ahodwo R/A	500	16	1	3.0	120.0
SWBL		Ahodwo R/A	245	7	1	3.3	
SWBT	Bekwai R/A	Santasi	1025	24	2	3.3	
SWBR		Sofoline R/A	450	5	1	3.0	120.0

Source: from study

CONCLUSION

Santasi roundabout was performing at full capacity based on the overall volume to capacity ratio. Santasi Roundabout should be signalized to control all the movements. It is cheaper to implement the signalised 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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BIOGRAPHIES

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