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Performance evaluation and redesign of Offa garage roundabout in Ilorin, Nigeria using microscopic simulation

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ABSTRACT

An urban traffic system is a composite network, consisting of varying types of intersections that interact dynamically under different traffic conditions. The management of these intersections is crucial, especially in heterogeneous traffic systems characterized by a mix of vehicle types and unpredictable traffic patterns. This paper focuses on such a system in Ilorin, Kwara State, Nigeria, where a non-signalized roundabout at a skewed T-intersection is proposed to be replaced by a signalized intersection to improve traffic management and reduce congestion. The study employs PTV VISSIM 21, a microscopic traffic simulation software widely used for evaluating traffic scenarios, to model the existing roundabout and simulate the proposed signalized intersection. By running simulations for both configurations, the analysis compares key performance metrics such as Level of Service (LOS), queue length, and vehicular emissions (CO2 and NO), which are critical indicators of traffic efficiency and environmental impact. Results from the simulations show that the signalized intersection significantly enhances traffic flow, reduces vehicle queue lengths, and lowers pollutant emissions compared to the current roundabout system. These improvements suggest that signaling the intersection can effectively address congestion and environmental concerns in the area. Based on these findings, this study recommends installing traffic signals at similar intersections in developing urban areas, particularly where non-signalized intersections are struggling to manage increasing traffic volumes

INTRODUCTION

The ever-increasing Nigerian population has given rise to a high demand for vehicles and hence there is a need for a proper, efficient and well-maintained transportation system. The rise in population and urbanization of the country without commensurate traffic management advancement has led to a low-level performance of most urban road networks in Nigeria (Adeleke et al., 2020). Traffic management should begin from the base levels and it should ensure safeness and convenience concurrently. Ilorin is the Capital of Kwara state, Nigeria and has witnessed tremendous development in recent years and thereby faces huge traffic rushes during the peak hours of the day. Effectively managing vehicular traffic flow is an important challenge for current-day societies, traffic means considerable costs for the populace and a great deal of effort is devoted in every big city to minimize the trouble caused by extreme numbers of vehicles (Mubasher and Qounain, 2015).

The difficulties of a traffic mode (such as, accidents, queues and pollutant emissions) are considerable at intersections. The intersection being the target of conflict in vehicular movements sometimes needs to be signalized. Signalized intersections are time-sharing, the different states of lights (green, amber or red) indicating the permission to go towards the intersection (green) or the need to stop before the junction (red) are used. Roundabout contrastingly is a space sharing that gives major priority to the rotational flow (Demir and Demir 2020).

Roundabouts have been used across the globe and are being the most used lately in Nigeria, as an element of urban areas for several past years but not every intersection and under all circumstances are roundabouts the perfect intersection control (Murat et al., 2021). There are situations under which roundabouts are not at all feasible, and certain times when they need to be considered with caution these are at times when intersection traffic flow is severely unbalanced which was observed at the Offa Garage roundabout

This paper discusses the performance of roundabouts and compares them to that of signal timing at the same intersection. The outcome of the study was able to indicate that, a signalized intersection will be more appropriate than the present rotary intersection and provides design parameters that would cater for future growth. Findings from the paper would serve as a basis for using VISSIM for the assessment of other roundabouts in Ilorin and Nigeria as a whole (Johnson and Hange 2015). PTV Vissim means "Verkehr in Städten SIMulationsmodell" (German for "Traffic in Cities Simulation Model"), is a traffic simulation software used to model and analyze traffic flow and road networks

STUDY AREA DESCRIPTION

The studied intersection is the Offa Garage rotary intersection, located in the Ilorin metropolis, on longitude N 8027'12.14" and latitude E 4034'52.20" (Google Earth Pro). The rotary intersection, shown in Plate 1, has three intersecting roads namely: Ita Alamu, Offa garage, and Asa dam road. Ita Alamu road has Through traffic towards Offa garage road, and the left turner goes around the roundabout to Asa dam road. Offa Garage has Through traffic (TT) towards Ita Alamu and right turner towards Asa dam road, while Asa dam road has right turners towards Ita Alamu and left turners towards Offa garage.

Plate 1: Satellite image of Offa Garage intersection

METHODOLOGY

Traffic volume is determined in the study using the videotaping method (Kwame et. al., 2014) using a camera phone mounted on a tripod stand and stationed at strategic locations on a high-rise building overlooking the intersection. The building is on the Ita Alamu axis; the position was identified from a reconnaissance survey as the most suitable position for the video recording. The study was conducted during AM and PM traffic peak periods to get the maximum possible number of vehicles. Peak hour volume count of vehicular movements in all the directions was thus obtained. The obtained heterogeneous vehicle count was classified, converted into a Passenger Car Unit (PCU) and used as input.

The recording was broken down into four intervals of 15 mins each for ease of recording. The traffic count was carried out for three days with the videotaping done at the morning peak hours (7:00 to 9:00 a.m.), midday (12:00 to 2:00 p.m.) and the evening peak hour (4:00 to 6:00 p.m.). The mid-day off-peak period is important so as to note the off-peak hours traffic volumes.

The traffic data collected was indicative of the existing peak-hour traffic conditions for the Offa garage roundabout. A single peak hour data for the intersection approaches was eventually used, for the analysis of comparing the existing non-signalized roundabout with when it is a signalized intersection.

Webster Method For Signal Timing

Webster method for signal timing is used. The Maximum signal cycle is given as (Webster, 1958):

$$C_0 = \frac{(1.5\ell + 5)}{1 - Y} \quad (1)$$

where,

C_0 = Maximum cycle time in seconds

ℓ = total time lost per cycle

$Y = y_1 + y_2 + y_3 + \ldots\ldots\ldots\ldots\ldots + y_n$

$y_1, y_2, y_3 \ldots.\ y_n$ are the ratios of flow to saturation flow $y_i = q_i / S_i$

where, q = total flow in $\frac{pcu}{hr}$

S = saturation flow =525w w = width of approach measured from curb to center line (m)

where, $y_1, y_2 \ldots$, yn are the critical flow ratios for phases 1, 2..., n.

L is given as

$$L = n\,(t + R) \quad (2)$$

where n = number of phases t = amber time for each phase

R = all-red clearance time provided for each phase.

RESULTS AND DISCUSSIONS

Signalized intersection replacement Data Analysis

Table 1: Traffic Data Collection (Peak hour Volume)

Routes	Volume pcu/hr
Offa Garage – Asa Dam R. T	675
Offa Garage – Ita Alamu T. T	1702
Ita Alamu- Offa Garage T. T	1813
Ita alamu – Asa Dam L. T	803
Asa Dam – Offa Garage L. T	813
Asa Dam – Ita Alamu R. T	521

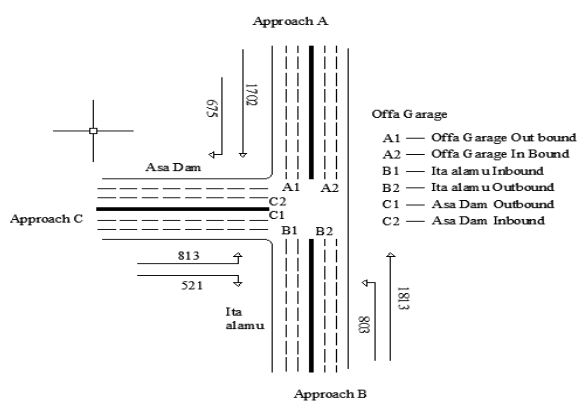

Figure 1: Schematic representation of vehicle distribution and directional movements

Using the value of t as 3 seconds of amber time and 2 seconds of all red clearance time for each phase

(MUTCD, 2009; Federal Highway Administration, 2008) and n = 3 (number of phases) in Eqn (2):

L = 3(3+2) = 15 seconds

Table 2: Software volume input

Intersection Lane	Direction of flow	Volume (pcu/h)	Total Volume (pcu/h)
Offa Garage Inbound	Ita Alamu – Offa garage T. T	1813	2626
	Asa dam – Offa garage L. T	813	
Offa Garage Outbound	Offa garage – Ita Alamu T. T	1702	2377
	Offa garage – Asa dam R. T	675	
Ita alamu Inbound	Asa dam – Ita Alamu R. T	521	2223
	Offa Garage – Ita Alamu T. T	1702	
Ita alamu outbound	Ita alamu- Offa Garage T. T	1813	2616
	Ita alamu – Asa dam L. T	803	
Asa Dam Inbound	Offa garage – Asa dam RT	675	1478
	Ita alamu – Asa dam L. T	803	
Asa Dam Outbound	Asa Dam – Ita alamu R. T	521	1334
	Asa dam – Offa garage L. T	813	

The critical flow ratios y_1, y_2 and y_3 as shown in Table 3 are 0.298, 0.132 and 0.131 respectively, thus Y for the three arms is obtained as

$$Y=y_1+y_2+y_3 \qquad (3)$$

which is

Y = 0.298+ 0.132 + 0.131 = 0.561

Therefore, $C_0 = \frac{1.5(15)+5}{1-0.561}$ = 62.6 secs ~ 63 secs

Maximum cycle time C_0 is 63 sec

Green time for the 3 phases is obtained as:

$$G_1 = \frac{Y_1}{Y}(C_0 - L) = \frac{0.298}{0.561}(63-15)$$ = 25.5secs (26 secs is used for design)

$$G_2 = \frac{Y_2}{Y}(C_0 - L) = \frac{0.132}{0.561}(63-15)$$ = 11.3secs (12 secs is used in design),

Table 3: Signal phase, Actual Capacity and Group Lanes

Phase	Movement	Critical Volume (pcu)	S = Saturation flow rate 525 w = S	Flow Ratio (y_i) v/s	Proposed Green Time (sec)
1	T.T from Offa garage T.T from Ita alamu	1813 1702	525 * 11.6 = 6090	0.298	26
2	L.T to Asa Dam from Ita alamu	803	525 * 11.6 = 6090	0.132	12
3	L. T from Asa Dam to Offa Garage	813	525 * 11.8 =6195	0.131	12

$$G_3 = \frac{Y_3}{Y}(C_0 - L) = \frac{0.131}{0.561}(63-15)$$ = 11.3secs (12 secs is used in design)

An allowable maximum cycle time of 65 is used for ease of calculation.

Figure 2: Diagram of Signal Timing

4.2 Modelling of the Present Condition and the Generation of a Redesigned Model for Proposed Replacement

There are 3 basic parameters used in PTV Vissim modeling, they are Vehicle input, vehicle compositions and vehicle routes.

i) Vehicle Input: The vehicle inputs show the number of vehicles that are simulated.

ii) Vehicle Composition: The vehicle composition includes the type of vehicles that are simulated i.e., Cars, Buses and Heavy goods vehicles (HGV); since tricycles can't be simulated, they are converted into passenger car units.

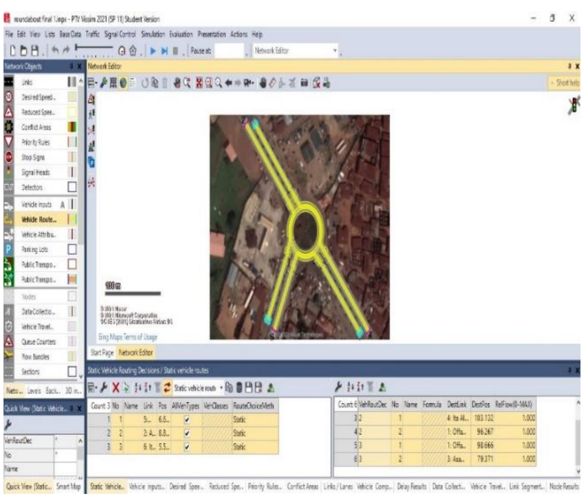

Figure 3a: Vehicle Input and Composition Roundabout

iii, Vehicle routes: This determines where a vehicle goes in a network, in the study there are 6 vehicular directional movements which include through traffic on Approach A Right turn to Approach C, Approach B has Through traffic and a left turn to Approach C while Approach C has a left turn to Approach A and right turn to Approach B as shown in Figure 3a and 3b for both the present condition and the proposed redesign.

Figure 3b: Vehicle input and composition for the proposed redesign replacement

Table 4: Node result unsignalized(roundabout) extracted for clarity From PTV VISSIM

Time Interval (sec)	Movement	Queue length (m)	Queue length max (m)	LOS	Stop delay (sec)	Emissions Co_x in (grams)	Emissions No_x (grams)	Emissions VOC (grams)	Fuel consumption (USGallons)
0 - 3600	A1 - B1	68.26	80.60	LOS E	9.83	142.312	27.689	32.982	2.036
0 - 3600	A1 - C2	68.26	80.60	LOS F	15.58	170.509	33.175	39.517	2.439
0 - 3600	B2 - A2	69.92	83.92	LOS F	14.95	363.686	70.76	84.288	5.203
0 - 3600	B2 - C2	69.92	83.92	LOS F	20.5	388.735	75.634	90.093	5.561
0 - 3600	C1 - A2	61.6	74.72	LOS F	36.6	316.234	61.528	73.29	4.524
0 - 3600	C1 - B1	61.6	74.72	LOS B	1.58	58.836	11.447	13.636	0.842
0 – 3600	Movement Summary	66.59	83.92	LOS F	16.5	1432.146	278.644	331.914	20.488

Table 4 shows the Summary for the present condition of traffic at Offa Garage roundabout during a typical peakiest hour for all movements.

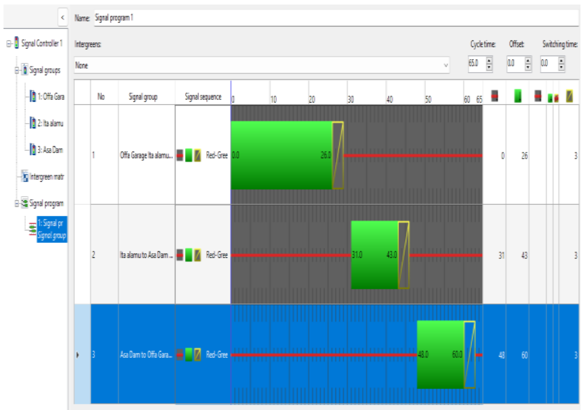

Figure 4: Signal Programming in PTV VISSIM

Figure 4 shows the scenario where the intersection was simulated by installing signal heads appropriately and calculating the cycle time using the Webster method the tabulated result in Table 5 was obtained

Table 5 shows the Summary for the signalized replacement of traffic at Offa Garage roundabout during a typical peakiest hour for all movements

Table 5: Node result signalized extracted from PTV VISSIM for clarity

Time Interval	Movement	Queue length	Queue length max	LOS	Stop delay	Emissions Co_2 in grams	Emissions Nox	Emissions VOC	Fuel consumption
0 - 3600	A1 - B1	20.85	115.14	LOS B	7.1	160.08	31.146	37.1	2.29
0 - 3600	A1 - C2	5.98	76.82	LOS A	2.42	131.712	25.626	30.526	1.884
0 - 3600	B2 - A2	28.05	116.84	LOS A	2.76	128.654	25.031	29.817	1.841
0 - 3600	B2 - C2	28.05	116.84	LOS A	2.19	158.004	30.742	36.619	2.26
0 - 3600	C1 - A2	26.41	68.55	LOS D	12.68	146.408	28.486	33.932	2.095
0 - 3600	C1 - B1	0.09	7.94	LOS A	1.86	42.75	8.318	9.908	0.612
0 - 3600	Movement Summary	16.28	116.84	LOS B	6.23	766.122	149.059	177.556	10.96

Figure 5 shows the signal head which helps communicate movements and control the flow of vehicles i.e., means the red yellow and green light at signal-controlled intersection. After manual calculation with Webster method a 3-signal phase/group was assigned, they are the Offa Garage and Ita Alamu T.T, Ita Alamu to Asa Dam Left turns, Asa Dam to Offa Garage Left Turns. The geometrics of the roundabout was redesigned and channelized as shown in Figure 5 to make sure Right Turners are not in any way hindered in their movement.

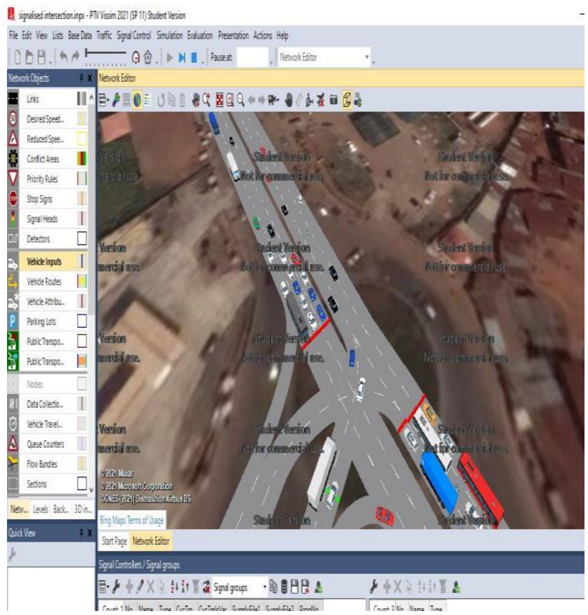

Figure 5: Signal Head Assigned

The result keywords include the following:

Time Interval: Time step of 1hr is converted to seconds.

Movement: the 6 possible directional movements in the roundabout are shown in Figure 3a.

Queue Length: Average queue length in each time interval, the current queue is measured and the arithmetic mean is thus calculated per time.

Queue Length Maximum: In each time step, the current queue length is measured and the maximum is thus calculated.

LOS(ALL): Level of service A-F as computed by the associated Level of service scheme.

VEH DEL (ALL): the delay of a vehicle in leaving a travel time measurement is obtained by subtracting the theoretical (ideal) travel time from the actual travel time.

STOP DEL (ALL): Stopped delay per vehicle in seconds without stops at PT stops.

Emission Cox: Emission Co quantity of carbon monoxide.

Emission NOx: Quantity of nitrogen oxides (grams)

Emission VOC: Volatile organic compounds (grams)

Discussion on redesigning the existing roundabout to a signalized intersection.

Using the maximum Traffic data experienced on each approach on the roundabout the following comparison are made

a) Using Level of Service

- Offa Garage Through traffic to Ita Alamu i.e. A1 to B1 presently operates at Level of Service (LOS) E but if replaced with the designed signalization it will operate at LOS B.
- Offa Garage Right Turn to Asa Dam i.e. A1 to C2 presently operates, at LOS F on the roundabout but if replaced with the signalized intersection it operates at LOS A
- Ita Alamu Through traffic to Offa Garage i.e., B2 to A2 presently operates at LOS F on the roundabout but if replaced with a signalized intersection it operates at LOS A
- Ita Alamu Left Turn to Asa Dam i.e., B2 to C2 presently operates at LOS F on the roundabout but also if replaced with a signalized intersection it operates at LOS A
- Asa dam Left Turn to Offa Garage i.e., C1 to A2 presently operates at LOS F on the roundabout but if replaced with a signalized intersection it operates at LOS D.
- Asa dam Right Turn to Ita Alamu i.e., C1 to B1 presently operates at LOS B on the roundabout but if replaced with a signalized intersection it operates at LOS A.

The Average level of service at the peak hour period is LOS F for the present situation in Offa Garage while for the scenario when replaced with a signalized intersection is LOS B

b) Using Queue length

The Queue length for the present peakiest hour condition is found to be generally higher in the present condition than when replaced by a signalized intersection.

- Movement A1 to B1 has an average Queue length of 68.26m for the Unsignalized roundabout and 20.85m for the Signalized intersection
- Movement A1 to C2 has an average Queue length of 68.26m for the Unsignalized roundabout and 5.98m for the Signalized intersection
- Movement B2 to A2 has an average Queue length of 69.92m for the Unsignalized roundabout and 28.05m for the Signalized intersection
- Movement B2 to C2 has an average Queue length of 69.92m for the Unsignalized roundabout and 28.05m for the Signalized intersection
- Movement C1 to A2 has an average Queue length of 61.60m for the Unsignalized roundabout and 26.41m for the Signalized intersection

- Movement C1 to B1 has an average Queue length of 61.6m for the Unsignalized roundabout and 0.09m for the Signalized intersection

Figure 6 shows the average Queue Length experienced in each movement for both the existing condition (Unsignalized) at the Offa Garage Intersection and when replaced with a Signalized intersection. It can be deduced that all the average queue lengths are generally higher without signalization experienced by a typical vehicle movement is mostly lower when signalized.

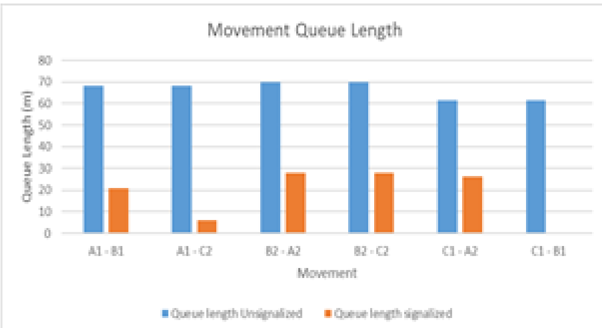

Figure 6: Queue Length for each movement

Using Emission: Harmful Emissions which include Carbon monoxide, Nitrogen monoxide, Volatile Organic Compound VOC, and fuel consumption are found to be higher in the present condition than when replaced by a signalized intersection

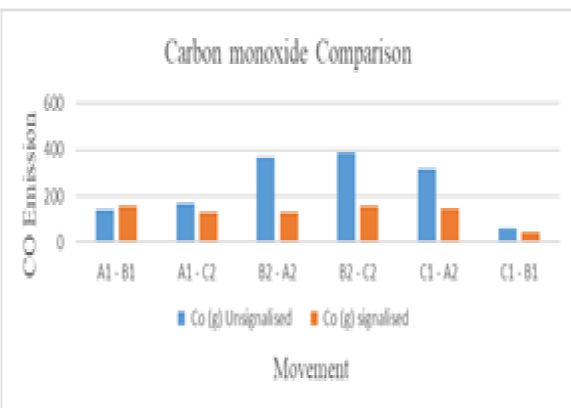

Figure 7: Carbon Monoxide Unsignalized and Signalized Intersection

Figure 7 shows the comparison of Carbon Monoxide Emissions for the Unsignalized and Signalized Intersection replacement. It can be deduced that for most of the movements on average more COx is emitted on unsignalized than when replaced with signals

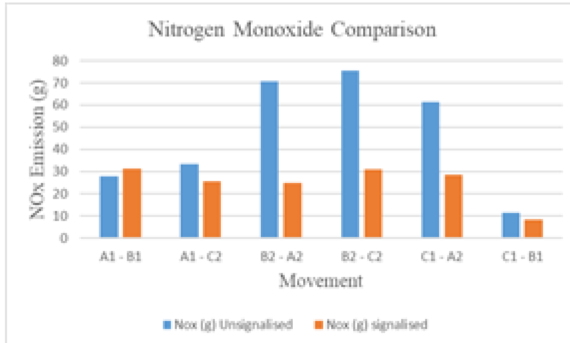

Figure 8: Nitrogen Monoxide Unsignalized and Signalized

Figure 8 shows the comparison of Nitrogen monoxide Emissions for the Unsignalized and Signalized.

CONCLUSION

At busy intersections in urban areas with heavy traffic, delays and congestion are common. To address this issue, it is crucial to enhance the traffic performance at such intersections. This study successfully designed a 3-phase traffic signal control scheme with an optimum cycle length of 63 seconds for the Offa Garage roundabout. The green times for phases 1, 2, and 3 are set to 26 seconds, 12 seconds, and 12 seconds, respectively, with an amber time of 3 seconds and an all-red clearance time of 2 seconds. The signal design enables smoother traffic flow, reduces conflicts at the intersection, and eliminates the need for traffic wardens. The redesign improved the Level of Service (LOS) for the Offa Garage intersection from LOS F to LOS B, with individual approaches having LOS B, A, and C for Offa Garage, Ita Alamu, and Asa Dam approaches, respectively.

RECOMMENDATION

It is recommended that intersection planning and design incorporate signalization where necessary to maintain an acceptable Level of Service (LOS) and accommodate future traffic growth. Proper signalization, using traffic micro-simulation tools, can provide critical insights into traffic patterns for specific environments, helping to manage congestion more effectively.

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