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ORIGINAL RESEARCH ARTICLE

CAPACITY AND PERFORMANCE ASSESSMENT OF WURUKUM ROUNDABOUT IN MAKURDI METROPOLIS: A COMPARATIVE STUDY USING ARCADY AND SIDRA INTERSECTION SOFTWARE

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ABSTRACT

Following the recent public outcry over delays and long queues at the Wurukum Roundabout Makurdi due to increase in travel demand at the road intersection, it is not certain if the performance of the roundabout is satisfactory based on engineering specifications and judgment. Therefore, simulation of the 5-arm at-grade intersection was carried out using Assessment of Roundabout Capacity and Delay (ARCADY) and the Signalised (and unsignalised) Intersection Design and Research Aid (SIDRA INTERSECTION) Software. The geometric dimensions of the roundabout were measured and manual traffic counts were used to obtain average travel demand matric from the morning (8:30 – 9:30 am) and evening (4:30 – 5:30 pm) peak periods, and heavy vehicle proportion of Origin-Destination (O-D) flows on the roundabout. Simulation models of the Wurukum roundabout were built using ARCADY and SIDRA INTERSECTION software to measure its capacity and performance based on key parameters such as Level of Service (LOS), average geometric delay and queue length among others. Though significant variations were observed among estimated performance indices, results obtained from the simulated models and statistical analysis (test of hypothesis using Chi-square test) indicated that the roundabout operates at failed state classified as LOS F at its present condition. Recommended strategies to improve the capacity and performance of the roundabout included any of the following; construction of a fly-over bridge connecting the Northern and Southern approaches as permitted by site physical features, signalisation of the roundabout with traffic signs, proper pavement markings and adjustment of its geometric features, or redesign and construction of road network within Makurdi metropolis to divert and reduce traffic demand on the roundabout

1.0 Introduction

An efficient roundabout is essential in the distribution of traffic to various routes of a traffic network for smooth flow at its optimum services. The performance of roundabout is a function of its capacity, driver behaviour, delay, queue lengths, Origin-Destination (O-D) flow, fuel consumption and pollution emission (noise and small particles), vehicles and pedestrians characteristics, Level-of-Service (LOS), and gap acceptance among others. (Akcelik, 2008; Dixit, 2012; Grossi, et al., 2012; Akcelik, 2017a; Yusuf et al., 2018). Furthermore, the capacity and performance of roundabout is also affected by its geometric features, driver behaviour, visibility, traffic characteristics, frequency of priority reversal act, etc. (Design Manual for Road and Bridges - DMRB, 2007; Akcelik, 2008; Findley et al., 2016: ARCADY, 2017). Previous researches have examined roundabout capacity and performance level using several methodologies (Highway Capacity Manual - HCM, 2010; Macioszek and Akcelik, 2017; Akcelik, 2017b).

Inefficient roundabout constitute congested traffic condition characterised by long queue lengths, high level of pollution, prolonged waiting time and consequently long travel times among others (Akcelik et al., 1996; Sheehan, 2010). These characteristics create unhealthy environment when it is saturated with pollutants, and also affects the social-economic wellbeing of commuters that are using the roundabout in terms of delays and abuse of value of travel time. Essential geometric parameters used for roundabout analysis include; average effective flare length, conflict angle, inscribed circle diameter, entry width, approach half width and entry kerb radius (Akçelik, 1997; DMRB, 2007; SIDRA INTERSECTION 8 User Guide, 2018).

The remedies of failed roundabout caused by high travel demand, O-D flow pattern or geometric dimensions include signalisation of the roundabout, conversion to grade separated intersection and adjustment of traffic network layout. Advantages of signalised roundabout include improved capacity and a balanced or evenly shared delay on approaches (Bernetti et al., 2003). The choice of converting an existing roundabout to a grade separated intersection or alteration of traffic network with the aim of decongesting a roundabout is usually capital intensive as it is relatively expensive and affects land use policies within the right-of-way.

The Wurukum roundabout is a 5-arm (including exit street) at-grade central intersection connecting cardinal parts of Makurdi metropolis by roads. Due to its central location in the metropolis, all traffic within the metropolis converge on the roundabout to link with other parts of the metropolis. It is not certain if the present performance status of Wurukum roundabout is satisfactory or gives hope for acceptable performance in the near future. Though unpublished, previous studies by the Department of Civil Engineering, Federal University of Agriculture Makurdi on the roundabout revealed that, traffic growth within Makurdi has increased drastically in recent times (DCE-UAM, 2017), thereby affecting the performance of the roundabout. Increased traffic volume is associated with congested traffic situation which generates negative transport externalities such as increased travel costs (fuel and delay), pollution, etc. (Sheehan, 2010; Gudmundsson et al., 2015).

There are several simulation software used for examining the present performance of road intersections or for future performance predictions. These models include; Assessment of Roundabout Capacity and Delay (ARCADY), Verkehr In Städten – Simulationsmodell (VISSIM) meaning Traffic in cities - simulation model in German, Highway Capacity Manual (HCM), Signalised (and unsignalised) Intersection Design and Research Aid (SIDRA) INTERSECTION software etc. (Vaiana et al., 2012; Akcelik, 2017a).

1.1 ARCADY Model

Like other roundabout capacity simulation models, the ARCADY software is used for simulation of roundabouts to predict capacity and performance as well as accident risk. ARCADY is a software built in the United Kingdom by Transport and Road Research Laboratory (TRRL) currently referred to as Transport Research Laboratory (TRL) based on regression models built from empirical studies of roundabouts in the UK for roundabout simulation (Brown, 1995;

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Akcelik, 1997; Akcelik, 2017b). The software examines the relationship between roundabout arm capacities as a function of its geometric dimensions and circulating flow which hinder vehicle entry on the circulatory roadway. The ARCADY model estimates roundabout arm capacity as a function of circulating flow using the relationship given as Equation 1;

$$Q_e = F_i - f_i Q_c \tag{1}$$

where, Q_e is the entry capacity (pcu/h), Q_c is the circulating flow (pcu/h), F_i and f_i are constants representing intercept and slop respectively, which are estimated from geometric characteristics of the roundabout. Capacity and performance analysis of roundabout using ARCADY software is based on approach or arm capacity (ARCADY, 2017).

Though ARCADY model was built after empirical examination of about 84 roundabouts in the UK within the period of 10 - 12 years based on UK's unique roundabout characteristics and driver behaviours, it is not out of place for other countries to examine its suitability in capacity and performance assessment as well as accidents risk with or without further calibrations as the case may be, since the software has undergone modifications over the years to suit other countries traffic system like Canada, USA, etc. (ARCADY, 2017).

Some researchers such as Akcelik (2011, 2017b) and Weber (2014), have criticised the suitability of ARCADY software for roundabout analysis in terms of capacity and performance prediction. Some of the critiques include; lane-by-lane modelling concept, that ARCADY considers entering traffic to be evenly distributed on the circulatory carriageway irrespective of the demand flow with respect to lane configuration on both entry and circulatory carriageways; this affects capacity estimation of roundabouts with irregular lane configuration (Akçelik, 2011; Akçelik, 1997). Its entry lane analysis model is based on simulation techniques rather than empirical studies hence generates unrealistic results (Weber, 2014). ARCADY's empirical capacity prediction is based on the geometry and circulating flow passing in front of an approach; it ignores other capacity mechanisms (Weber, 2014; Akçelik, 2011). The Gap-acceptance theory and driver behaviour or traffic flow theorem are not considered by ARCADY; hence predictions are incorrect since in reality, there are several anomalies such as priority reversal which might halt circulating traffic to standstill (Akçelik, 2011). Finally, the calibration of ARCADY model is based on geometries considered in the LR942 study, hence results are prone to errors when used on other roundabouts (ARCADY, 2017). In spite of the above criticism, the adoption of ARCADY by this study is justified by the fact that, the geometry of roundabout and driving rules in the UK are akin those in Nigeria (Federal Ministry of Works, 2013).

Following the previous empirical studies, ARCADY software was found to use the average vehicle length of 5.75 m and specified average threshold values of 0.85 for volume/capacity ratio or degree of saturation beyond which the performance of an arm is classified as having LOS F, meaning it has failed. An average of 36 seconds delay and 20 veh. for queue lengths are used as acceptable thresholds for good performance. Required geometric parameters for roundabout simulation using ARCADY software included; approach half and entry widths, average effective flare length, entry angle, entry kerb radius and inscribed cycle diameter. These parameters were measured on site using guidelines stated in the Design Manual for Roads and Bridges (DMRB) (2007) as shown in Figure 1.

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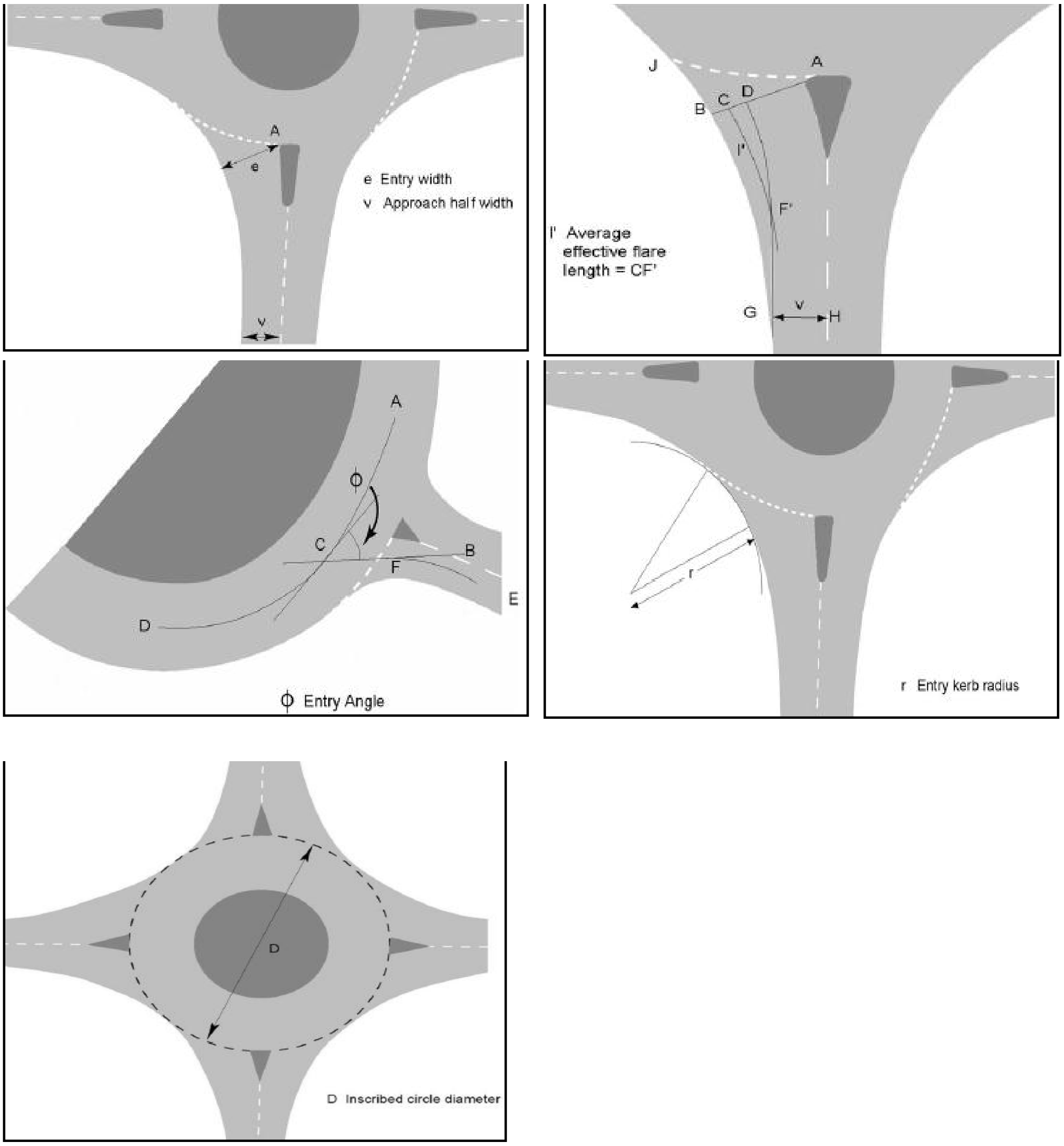


Figure 1: Definition of Roundabout Features (DMRB, 2007)

1.2 SIDRA INTERSECTION Model

On the other hand, SIDRA is an acronym for Signalised (and unsignalised) Intersection Design and Research Aid. SIDRA INTERSECTION is a simulation software first released in 1984 used for road intersection analysis and design. It is an advanced lane based and driver-path micro-analytical tool used for capacity and performance analysis of stand-alone intersections and network of intersections, including modelling of separate movement classes of vehicles ranging from light vehicles, heavy vehicles, buses, bicycles, large trucks, light and rails/trams etc. The SIDRA INTERSECTION software analyses intersections using lane-based micro-analytical approach on stand-alone intersections or in a given road network considering different types of vehicles and dynamic human behaviour. Its roundabout capacity model considers the effects of O-D pattern of flow, lane usage (utilisation) on multiple-lane approaches with heavy and unbalanced flows. The capacity and performance models of SIDRA INTERSECTION were calibrated using real-life and simulation data. The use of SIDRA software for intersection analysis has been commendable over time. The software is capable of estimating intersection performance measures such as capacity, LOS, delay (geometric or operational), queue length and stops for vehicles and pedestrians, fuel consumption of all vehicles using the roundabout in terms of cost ($/km) and rate (L/100km), amount of emitted air pollutants from vehicles tail pipe such as carbon dioxide, hydrocarbon, carbon monoxide, nitrogen oxides in kg/hour, performance index estimated from the combined statistics of server variables, etc. The SIDRA INTERSECTION software within its framework provides operational alternatives of using the HCM models for estimating essential performance variables. According to the SIDRA INTERSECTION 8 User Guide (2018), using its micro-analytical technique, the gap acceptance lane capacity in SIDRA INTERSECTION is estimated using Equation 2;

$$Q = s.u \qquad 2$$

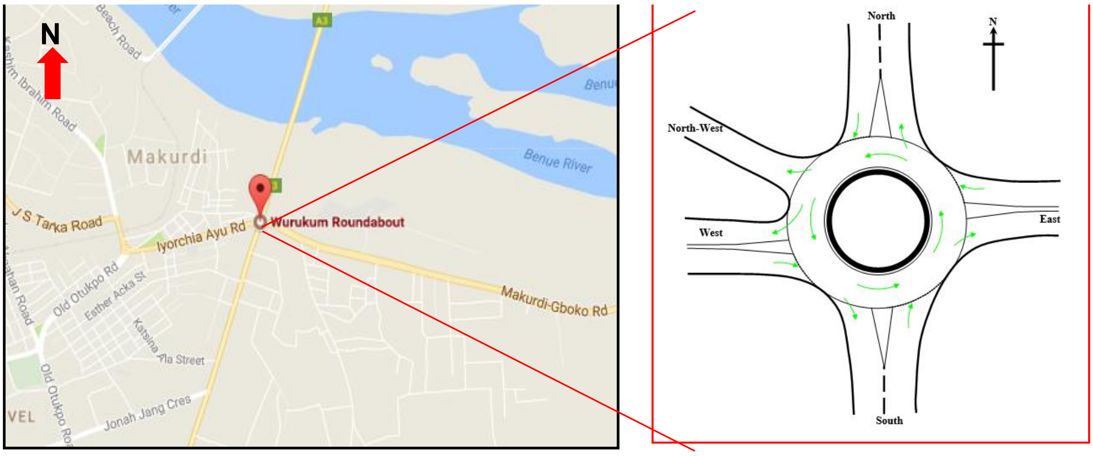
where, Q is the capacity of a given lane (veh./h), s is its saturation flow rate expressed as $3600/t_f$ (veh./h), where t_f is defined as the follow-up headway (sec.), and u is the unblocked time ratio. The unblocked time ratio is the proportion of time when vehicles can depart from the queue of a specified lane. Though researches on the suitability and improvement of the SIDRA software for intersection analysis and design stated long ago, works on its improvements are still ongoing (Akcelik et al., 1998; Akcelik, 2008). The software has gain wide acceptance around the world from transport infrastructural planners and development experts over the years in USA, Europe, Australia, South Africa, New Zealand, Malaysia, Singapore, Latin America and Arabian Peninsula (SIDRA INTERSECTION 8 User Guide, 2018).

The aim of this study is to carry out a comparative study on capacity and performance assessment of the Wurukum roundabout using ARCADY 9 and SIDRA INTERSECTION 8 software. Specific objectives of the study included the assessment of the geometric features and travel demand pattern on the roundabout using guidelines specified in the ACARDY 9 and SIDRA INTERSECTION 8 user manuals, and simulating the capacity and performance of the roundabout using ARCADY and SIDRA INTERSECTION based on its present status. Solutions to improve the roundabout's performance if found inefficient were proposed.

2.0 Materials and Methods

2.1 The Study Area

Makurdi is the capital city of Benue state in Nigeria. It falls within the North-central geopolitical zone of Nigeria. Makurdi metropolis lies on the Benue trough linking the North and Southern parts of Nigeria within Latitudes 7°50'20''N and N7°37'60''N and Longitudes 8°19'30''E and E8°40'20''E. The Wurukum roundabout site is situated at 7° 43' 56" N and 8° 32' 21"E coordinates (Google Earth, 2017). According to the 2006 national population census (NPC, 2006), Makurdi metropolis has an estimated human population of 367,588 persons with a landmass of approximately 800 km^2. The metropolis is separated by the River Benue into Makurdi-North and Makurdi-South. The population of the metropolis is dominated by civil servants, business men and women, and students. The location of Wurukum roundabout in the Makurdi metropolis is as shown in Figure 2.



(a) Extract Map of Makurdi metropolis (Google Earth, 2017) (b) Layout of Wurukum Roundabout

Figure 2: Layout of the Wurukum Roundabout

Road network in Makurdi metropolis is aligned such that all major routes link to the central roundabout which receives and distributes influx and exit traffic respectively within the metropolis. The symmetrical nature of road network in Makurdi metropolis made the study of traffic flow pattern simple since all major routes within the city are linked to a common central intersection called the Wurukum roundabout. The roundabout connects traffic from the North (N), West (W), South (S) and East (E) approaches namely Lafia road, Iorchia Ayu road, Otukpo road and Gboko road respectively. There is also an exit street named Onitsha Street between the North and East (NE) approaches. Traffic streams within Makurdi metropolis basically consist of private cars, motorcycles (Okada), tricycles (Keke Napep), minibuses, taxicabs and trucks, meant to convey people, goods and services from one place to another.

2.2 Data Collection

The geometric dimensions of Wurukum roundabout were measured using steel measuring tape and protractors. Essential parameters measured included; Entry width (e), Approach half width (v), Average effective flare length (l'), Entry angle (ϕ), Entry kerb radius (r) and the Inscribed circle diameter (D). A classified daily manual traffic count was carried out from 06:00 am to 06:00 pm to obtain Average Daily Traffic (ADT), and percentages of heavy vehicles based on O-D flows on the roundabout using writing materials for a period of two weeks with emphasis on morning (8:30 – 9:30 am) and evening (4:30 – 5:30 pm) peak periods. The average hourly traffic demand for morning and evening peak periods were obtained for all arms to generate average travel demand and percentage of heavy vehicles matrices based on Passenger Car Unit per hour (pcu/h) of travel demand.

2.3 Development of ARCADY Model

A simulation model of Wurukum roundabout was built at the University of Leeds, United Kingdom using ARCADY software based on its geometric parameters and travel demand matrix, as well as the percentage proportion of heavy vehicles. The built ARCADY model was simulated to examine its performance. Essential performance parameters targeted included; maximum average queue length, maximum delay, volume/capacity ratio and LOS which collectively defined performance of the roundabout in the context of ARCADY software.

2.4 Development of SIDRA INTERSECTION Model

Development of the SIDRA INTERSECTION models involved the use of some input parameters characterising the site layout (same as for ARCADY model) and traffic behaviour and flow at the Wurukum roundabout were specified under the movement definition, lane geometry, lane movement, travel demand and the vehicle movement data tabs. Default settings for all exits lanes under the lane movements tab were ignored since the site was analysed as a standalone site and not a whole network. Also, pedestrians' behaviour at the roundabout were not considered. A simulation run of the configured system yielded detailed output results which described the performance of the roundabout. The diagnostic section of detailed output reports were used to check errors and troubleshoot during simulation iterations.

2.5 Statistical Analysis for Fitness Test

The Chi-squared test at 5% level of significance was used to test the performance similarity of both models with a null hypothesis of being equal to aid decision of the analysis.

3. Results and Discussion

3.1 Site Geometry and Traffic Flow Rate

The geometric dimensions and O-D flow rate matrix based on adjusted travel demand using Peak Hour Factor (PHF) on Wurukum roundabout for year 2016 were as shown in Tables 1 and 2 respectively.

Table 1: Geometric Dimensions of Wurukum Roundabout

Approaches	No. of Lanes	v (m)	e (m)	l' (m)	r (m)	D (m)	ϕ (0)
S	1	5.50	8.80	29.20	38.10	50.00	17.00
E	2	7.80	13.90	21.00	17.65	50.00	13.00
N	2	6.20	12.90	20.10	10.85	50.00	15.00
W	2	8.80	12.10	24.50	33.64	50.00	24.00
NW	2	6.15	12.00	-	-	50.00	-

Table 2: Average O-D Flow Matrix (PCU/h)

Approaches	S	E	N	W	NW	Total Origin
S	-	1223	337	425	24	2009
E	221	-	455	1110	103	1889
N	166	537	-	853	397	1953
W	722	1385	684	-	-	2791
Total Destination	1109	3145	1476	2388	524	8642

The N and S traffic volume travelled on undivided road corridors with relatively narrow lanes as shown in Table 1. The average flare length which served as storage spot for waiting vehicles on all approaches ranged between 20 – 30 meters. Table 2 shows that, average total travel demand on the roundabout within the study period was 8642 pcu/h, with the W corridor carrying relatively high volume of traffic followed by the N. Approach E has the least volume of traffic lower than N approach.

The percentage of heavy vehicle demand matrix on the Wurukum roundabout was as shown in Table 3, with S and N approaches having relatively high percentages of heavy vehicles.

Table 3: Demand Percentage of Heavy Vehicles

Approaches	S	E	N	W
S	-	2.4	3.2	0.01
E	1.1	-	2.2	0.01
N	2.9	1.8	-	0.02
W	0	0.1	0.01	-

This proportion distribution is attributed to the haulage of oil and gas products as well as agricultural products from the southern to northern part and vice versa in Nigeria.

3.2 Simulation Results

The summary of simulation results for ARCADY 8 (ADY) and SIDRA INTERSECTION 8 (SDI) software were as shown in Table 4.

Table 4: Summary of Simulation Results

Legs	Average Delay (s)		Average Queue (veh.)		Degree of Saturation		LOS		Junction Delay (s)		Junction LOS	
	ADY	SDI	ADY	SDI	ADY	SDI	ADY	SDI	ADY	SDI	ADY	SDI
S1		4861		1140.0		6.37		F				
SA	9657	4861	1691	3267	3.53	6.37	F	F				
E1*		123.1		75.8		1.08		F				
E2*		117.3		87.9		1.08		F				
EA*	5	120	3	87.9	0.74	1.08	A	F				
N1		816.7		212.6		1.87		F	2511	1498	F	F
N2		808.0		294.6		1.87		F				
NA	164	812	89	294.6	1.10	1.87	F	F				
W1		369.9		303.5		1.39		F				
W2		372.8		254.0		1.39		F				
WA	340	371	250	303.5	1.18	1.39	F	F				

* Subscripts 1, 2 and A define the inner lane, outer lane and maximum weighted average results respectively for the S, E, N and W approaches of the SIDRA INTERSECTION iterations.

Table 4 presents parameters used for performance examination based on outputs of ARCADY and SIDRA INTERSECTION software. ARCADY model presents average results for entire approach, while the SIDRA INTERSECTION software presents results for lane-by-lane analysis of each approach. Both software yielded approximately similar results for lane degree of saturation, lane LOS, junction delay and junction LOS variables which described performance of the roundabout. Using the average threshold values specified by the models, Table 4 revealed that the performance parameters of the roundabout for approaches N, W and S showed poor performance using both models, which indicated a failed performance at LOS F. From the ARCADY model, the maximum average delay and queue length on approaches showed that performance of the S approach was relatively worse compared to the N and W approach lanes. The E approach performed relatively better compared to the N, W and S approach lanes. This was due to the degree of saturation of all lanes constituting the N, W and S approaches being greater than the weighted average threshold of 0.85 units defined by ARCADY model. Though the combined effects of lanes for the E approach had degree of saturation of 0.74 units which was less than the threshold, hence was the only approach performing within permissible LOS at present. Based on analysis using the ARCADY model, though approach E performed at LOS A, the failure of approaches N, S, and W to attain fair LOS affected the performance of the entire roundabout leading to its failed status. Therefore, based on these performance parameters, ARCADY software described the holistic performance of the roundabout at LOS F.

On the other hand, results obtained from simulations using the SIDRA INTERSECTION software also showed some similarities to those obtained using ARCADY software, as shown in Table 4. Though the analysis carried out by the SIDRA INTERSECTION model were on a lane-by-lane bases, results presented in Table 4 showed both the lane and approach performance estimated as the weighted averages of the lanes performance. This average is defined as the weighted averages of iteration runs for individual lane performance per approach (Akcelik, 1996, 1997; SIDRA INTERSECTION 8 User Guide, 2018). Results obtained from the E approach indicated a relatively good performance which conformed to findings of the ARCADY models, though still classified as failed at LOS F by the SIDRA INTERSECTION models. These results indicate slight similarity with those of the ARCADY models which classified the E approach at LOS A since other performance parameters such as maximum average delay and queue length of the E approach showed relatively low magnitude as compared to the N, W and S approaches. Based on these performance statuses, the SIDRA INTERSECTION software classified the Wurukum intersection at LOS F which conforms to results of the ARCADY Software.

The test of hypothesis using chi square statistical test for similarity of results between the ARCADY and SIDRA INTERSECTION models at 5% level of significance and 3 degree of freedom with a null hypothesis of both being equal is as shown in Table 5;

Table 5: Statistical Analysis – Chi Square Test

Models	Chi Square ($\chi 2$) Values		Decision
	Computed	Critical	
Average Delay (s)	5361.79	7.81	Rejected
Average Queue (Veh.)	320.85	7.81	Rejected
Degree of Saturation (%)	1.72	7.81	Accepted

Table 5 also shows significant variations in the magnitude of performance outputs estimated using the ARCADY and SIDRA INTERSECTION models. Differences between the estimated average delay and average queue length per approach leading to rejection of the null hypotheses was attributed to the fact that, while SIDRA INTERSECTION model carried out lane-by-lane analysis of the intersection which required detailed lane specifications such as flow distribution proportion, lane utilisation, etc. (SIDRA INTERSECTION 8 User Guide, 2018), the ARCADY model carried out holistic analysis of the entire roundabout based on approach characteristics regardless of lane-by-lane properties to arrive at overall performance of the intersection (ARCADY, 2017). There was no significant difference in the estimated degree of saturation of both models leading to acceptance of the null hypothesis, hence the parameter confirm similarity in travel demand situation considered by both models (Akçelik, 1996; 1997).

4. Conclusion

A simulation and comparative analysis of the 5-arm at-grade Wurukum roundabout situated in Makurdi metropolis using ARCADY and SIDRA INTERSECTION software was carried out. The simulation results revealed that, there were statistically significant differences between estimated average delay and average queue lengths on approaching lanes by both models, leading to rejection of the null hypotheses. On the other hand, there was no significant difference between estimated degrees of saturation from both models, hence the null hypothesis was accepted. Also, both models described the holistic performance of the roundabout at its present state as LOS F characterized by prolonged waiting times and long queue lengths on its approaches, especially the N, W and S approaches. In spite of variations in estimated outputs of the models which depended on different mathematical models used, results of the simulation analysis using the two software proved the failed status of the roundabout at LOS F. It was therefore concluded that, the Wurukum roundabout has failed based on its performance tests using ARCADY and SIDRA INTERSECTION software, hence calls for reengineering for improved performance.

The following recommendations were made;

Following the successes of using fly-over bridges to improve roundabout performance as stated in previous studies, this study therefore recommends the construction of a Fly-over bridge connecting the N and S approaches of the roundabout to separate traffic streams and ease traffic flow as permitted by land use policy on the site.

Signalisation of the roundabout with road signs and proper pavement markings as well as alteration of geometrical features – expansion of weaving length on all legs and additional lane on the S approach will help increase its capacity and performance thereby eliminating high cost of compensation and major re-construction works on the site.

Alteration of the entire road network in Makurdi metropolis to redirect and reduce traffic demand on the roundabout will reduce high traffic demand significantly, hence improve its performance.

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