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Comparative Assessment of Urban Intersection Performance under Varying Traffic Demands in Ilorin, Kwara State, Nigeria

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***Abstract*:** *Efficient operation of urban intersections is fundamental to achieving safe, reliable, and sustainable mobility in modern cities. This study evaluates the operational performance of eleven major intersections in Ilorin, Nigeria, comprising roundabouts, four-legged, and three-legged junctions. The study pursued two objectives, which are to assess the influence of geometric design characteristics and approach-specific traffic flow patterns on intersection performance and to compare the operational efficiency of different intersection types under peak traffic conditions. Field data were collected over a seven-day period using continuous video recording, capturing key geometric and traffic parameters including lane width, turning radius, turn-bay length, and approach volumes. These data were analysed using manually applied [2] procedures to estimate average delay, queue length, and level of service (LOS). Results indicate notable performance variations among intersection types. Roundabouts exhibited comparatively better operational performance, operating within the [2]-defined LOS D range with an average control delay of 37.3 seconds per vehicle. Four-legged intersections showed moderate performance, while three-legged intersections experienced the highest delays (mean = 51.2 s) and queue lengths extending up to 70 m. Statistical analyses using one-way ANOVA, Tukey's HSD, and regression modelling revealed significant differences in delay across intersection types ($p < 0.05$). Although the chi-square test indicated a weak association between intersection form and LOS classification, the overall findings suggest that, under the observed traffic and geometric conditions, roundabouts demonstrate greater operational resilience. Accordingly, the adoption of roundabouts is recommended as a traffic management measure tailored to comparable urban settings in developing regions, rather than as a universally applicable solution.*

Keywords: *Intersection performance, traffic delay, queue length, anova, urban traffic efficiency, highway capacity manual.*

1. INTRODUCTION

Efficient management of urban intersections is fundamental to achieving safe, reliable, and sustainable mobility in rapidly expanding cities. With accelerating urbanization, particularly in developing regions, the disparity between increasing traffic demand and the limited capacity of existing road infrastructure has led to persistent congestion, extended travel delays, and elevated crash occurrences [1][2]. Intersections function as pivotal nodes within transportation networks; however, they are also the most complex and conflict-prone segments where multiple traffic streams converge with varying speeds and priorities. Consequently, their effective design and control are central to maintaining operational fluidity, traffic safety, and overall network sustainability.

Intersections are broadly classified as either controlled or uncontrolled, based on the presence or absence of traffic management devices such as signals, roundabouts, or stop signs. Among the controlled types, roundabouts have gained widespread recognition for their operational and safety efficiencies. By facilitating continuous, one-way circulatory flow and moderating vehicular speeds, roundabouts substantially reduce the number of potential conflict points, minimize crash severity, and enhance overall capacity utilization [3][4]. Nevertheless, the comparative performance of roundabouts, signalized, and unsignalized intersections differs by context and is influenced by factors such as geometric layout, traffic composition, and adopted control strategies. A thorough understanding of these context-sensitive dynamics is therefore essential for data-driven intersection design and management.

Intersection performance assessments typically rely on core traffic flow parameter, such as average delay, queue length, degree of saturation, and Level of Service (LOS), which collectively indicate operational efficiency. Reliable estimation of these measures provides vital insights for capacity evaluation and performance diagnosis. Variations in geometric configuration, turning movements, or demand levels can substantially alter these indicators, ultimately

determining the efficiency and safety outcomes of the intersection [2].

Recent progress in analytical and simulation-based modeling has enhanced the precision and comprehensiveness of intersection performance evaluations. Simulation platforms such as SIDRA Intersection enable the examination of diverse geometric layouts, traffic control schemes, and flow conditions while incorporating variables such as turning proportions, saturation flow, and vehicle classification. Several studies [5][6][7] have validated SIDRA's effectiveness in optimizing signal timing, assessing turn-bay length effects, and improving LOS through model calibration and sensitivity testing. Similarly, other works [8][9] have demonstrated its capability in analyzing queue spillback, short-lane metering, and coordinated offsets across varying traffic demand scenarios.

Contemporary research has further extended these applications to more complex and dynamic urban contexts. For instance, [10][11] explored the effects of adverse weather and limited visibility on intersection capacity, while [12] emphasized the importance of heavy-vehicle equivalency adjustments in enhancing delay prediction accuracy. Likewise, [13] investigated multimodal operations and adaptive signal phasing techniques, revealing notable improvements in both throughput and person-based LOS. More recent studies (2024–2025) have incorporated the influence of connected and automated vehicles (CAVs), electric vehicle (EV) penetration, and transit signal priority mechanisms [14][15], reinforcing SIDRA's growing importance in the transition toward intelligent and sustainable urban mobility systems.

Addressing these emerging knowledge gaps, the present study evaluates intersection performance metrics and operational efficiency under varying traffic demand conditions. The research focuses on selected intersections within Ilorin, Nigeria—representative of a typical developing urban environment characterized by heterogeneous traffic flow and infrastructural constraints.

2. LITERATURE REVIEW

2.1 Overview of Intersection Performance and Efficiency

Several studies have demonstrated the applicability of SIDRA Intersection for analysing mixed traffic conditions when appropriate calibration is undertaken. [16], the developer of SIDRA, explains that the software incorporates flexible gap-acceptance, lane-utilisation, and follow-up headway models that can be adjusted to reflect heterogeneous traffic streams. SIDRA allows the modification of passenger-car-equivalent (PCE) values, critical gap parameters, heavy-vehicle proportions, and approach-specific behaviour factors, enabling representation of non-uniform vehicle interactions typical of mixed traffic environments. Empirical applications in developing countries further validate this capability.

[17] successfully calibrated SIDRA to model mixed traffic at urban intersections in India by adjusting PCEs and saturation flow parameters, achieving close agreement between observed and simulated delays. Similarly, [18] applied SIDRA under heterogeneous traffic conditions in Nigeria and reported that calibrated SIDRA outputs were consistent with field-measured queue lengths and delays. These studies provide clear evidence that, although originally developed for lane-disciplined traffic, SIDRA can reliably model mixed traffic operations when locally calibrated traffic and behavioural parameters are incorporated.

Intersections constitute critical nodes in transportation networks where multiple traffic streams merge, diverge, or cross. Their operational efficiency significantly influences travel time, fuel consumption, road safety, and the overall reliability of urban mobility systems. Intersection performance is typically measured using parameters such as delay, queue length, degree of saturation, and Level of Service (LOS), which collectively describe the interaction between traffic demand and available capacity [2]. According to [1][4], the widening gap between the rapid growth in vehicle ownership and the relatively static road capacity, particularly in urban centers, has intensified congestion levels and increased crash exposure at intersections.

Over time, intersection performance assessment has shifted from basic field observation toward simulation-driven analysis, offering a more robust representation of geometric, traffic, and control interactions. Advanced analytical platforms such as SIDRA Intersection, VISSIM, AIMSUN, and Synchro are widely utilized to simulate intersection operations under different traffic demand levels and control scenarios. Among these tools, SIDRA Intersection is distinguished for its ability to model mixed traffic, integrate environmental and economic indicators, and evaluate multiple control strategies concurrently [19][5].

2.2 Geometric Design and Traffic Control Characteristics

The geometric layout of an intersection, including approach width, turning radius, number of lanes, entry angle, and median configuration, plays a decisive role in determining its operational efficiency. Poor geometric alignment can increase vehicular delay, reduce capacity, and elevate crash likelihood by generating complex conflict zones [2]. Research works such as [7][6] revealed that optimizing geometric elements such as turn-bay length and entry flare width can substantially improve saturation flow and minimize queuing. Conversely, insufficient channelization and excessive entry angles often lead to inefficient gap acceptance and longer vehicle delays.

The control type adopted, whether signalized, unsignalized, or roundabout, also exerts a major influence on intersection performance. According to [3], roundabouts promote uninterrupted circulation and can reduce the number of potential vehicle conflict points by up to 75% compared to signalized junctions. Similarly, [4] demonstrated that roundabouts result in 20–40% shorter delays and 60–80% fewer severe crashes relative to conventional intersections. Nonetheless, their efficiency is highly dependent on proper geometric calibration,

particularly entry deflection and circulating lane configuration.

2.3 Analytical and Simulation-Based Performance Assessment

The Highway Capacity Manual (HCM) [2] remains the most widely referenced guide for estimating intersection capacity and LOS, offering standardized procedures for both signalized and unsignalized control types. However, its direct application in mixed-traffic environments, typical of many developing cities, has proven challenging due to irregular driving behaviors and significant non-motorized traffic interactions. Consequently, simulation-based approaches have become essential for performing context-sensitive evaluations.

Among available microsimulation models, SIDRA Intersection has been extensively validated for operational analysis. As noted in [19], it effectively computes vehicle delay, queue length, and stop frequency while incorporating energy and emission indicators such as fuel consumption and greenhouse gas output. Studies by [5][7] applied SIDRA in Nigerian and Ghanaian contexts to analyze the effects of signal phasing and turning movement ratios. Their results showed that calibrating the model with locally observed saturation flow rates enhances prediction accuracy and better represents heterogeneous traffic behavior.

2.4 Roundabout Versus Signalized and Unsignalized Intersections

Roundabouts have emerged as a preferred design alternative globally because of their safety and operational advantages. In a comparative microsimulation study, [20] found that roundabouts achieved lower average delays and reduced vehicle conflicts than both signalized and unsignalized intersections, even under fluctuating demand conditions. Similarly, [21] analyzed conventional and turbo-roundabout configurations, reporting that turbo-roundabouts delivered 15–30% higher capacities and shorter queues due to improved lane discipline and minimized weaving maneuvers.

In developing contexts, however, these advantages are often limited by poor geometric standards, weak driver compliance, and inadequate maintenance. A comparative analysis by [22] found that while roundabouts performed better than protected U-turn intersections under moderate volumes, their efficiency deteriorated at higher traffic levels because of poor gap acceptance. Supporting this, [23] identified intersection type as the strongest predictor of average delay, followed by approach width and entry flow rate in regression-based evaluations. Collectively, these studies affirm the superiority of roundabouts in most traffic scenarios, though their benefits depend on localized design calibration, behavioral factors, and demand characteristics.

2.5 Intersection Performance in Heterogeneous and Developing City Conditions

Intersections in developing cities often operate under conditions markedly different from those assumed in traditional traffic models. Common features such as weak lane discipline, high pedestrian interference, mixed vehicle composition, and unreliable signal systems complicate performance prediction [24][25]. For instance, [26] reported that non-lane-based movements in Pakistan caused SIDRA-predicted capacities to overestimate observed field capacities by 15–25%. Similarly, Wang and Luo (2025) found that adaptive offset tuning and short-lane metering could improve performance in Chinese intersections, though their effectiveness varied significantly with compliance levels and mode mix.

Empirical studies in sub-Saharan Africa remain limited. Investigations by [7][5] emphasized the importance of field-calibrated saturation flow and driver behavior parameters in achieving realistic simulation outcomes. Their analyses revealed that locally adjusted parameters reduced residual errors in predicted delays. Moreover, [25] observed that explicitly accounting for pedestrian and motorcycle interactions within SIDRA's multimodal framework improved model accuracy under Nigerian traffic conditions. These findings underscore the need for region-specific calibration and validation to enhance the applicability of global traffic models in African cities.

2.6 Environmental and Sustainability Dimensions

Sustainable intersection design encompasses not only operational efficiency but also energy conservation and emission reduction. Intersections characterized by frequent stopping and idling contribute disproportionately to fuel consumption and urban emissions [26][27]. Optimizing intersection design, particularly through roundabouts, can therefore play a major role in reducing CO_2 and NO_x emissions. In one study, [28] integrated emission models into SIDRA and demonstrated a 12–20% decrease in fuel usage for optimized roundabouts compared to signalized controls.

Aligning intersection design with sustainability principles also advances United Nations Sustainable Development Goal 11 (Sustainable Cities and Communities), which promotes environmentally responsible and inclusive mobility systems. Studies by [15][13] further corroborated that improvements in intersection performance generate co-benefits such as reduced greenhouse gas emissions, better air quality, and enhanced urban livability. Thus, embedding intersection efficiency within the sustainability framework ensures that operational interventions also contribute to broader environmental and societal objectives.

2.7 Research Gaps and Justification

Despite considerable progress in intersection performance modeling, notable research gaps persist, especially within developing urban environments. First, most prior studies have been conducted in high-income settings with uniform traffic conditions and advanced signal technologies. Second, empirical validation of SIDRA-based models under the mixed and informal traffic behaviors common in African cities remains limited. Third, limited integration exists between geometric calibration, control-type differentiation, and traffic composition when evaluating intersection performance across entire networks. Table 1

shows the summary of related empirical studies on intersection optimization.

To bridge these gaps, this study investigates the performance of eleven intersections in Ilorin, Nigeria—comprising roundabouts, three-legged, and four-legged configurations. Using field data and ANOVA statistics to examines how geometric characteristics, approach-specific flow, and control type affect delay, queue length, and LOS. The findings aim to validate international modeling approaches within developing city conditions, providing context-specific insights for sustainable intersection design and data-driven traffic management policy in sub-Saharan Africa.

Table 1: Summary of related empirical studies on intersection optimization

Authors (Year)	Focus Area	Key Findings
[5]	Signal timing and cycle length optimization	The study demonstrated that optimized signal cycle lengths effectively minimized control delays by approximately 12–16% at critical volume-to-capacity conditions.
[6]	Turning ratio sensitivity at T-intersections	Findings revealed that increased right-turn movements substantially deteriorate the Level of Service (LOS) for minor approaches, emphasizing the need for turn-based capacity adjustments.
[7]	Queue spillback prediction and offset coordination	Coordinated signal offsets were shown to reduce queue spillback by up to 18%, resulting in smoother progression and improved overall corridor efficiency.
[8]	Roundabouts versus signalized intersections under variable peak demand	Roundabouts consistently exhibited superior operational performance during moderate traffic conditions compared to signalized junctions.
[9]	Saturation flow calibration for mixed traffic environments	Local calibration of saturation flow parameters enhanced model precision, improving the accuracy of delay and Degree of Saturation (DoS) estimations.
[29]	Data-driven offset optimization	Implementation of adaptive arrival-based coordination strategies reduced the number of vehicle stops along urban corridors by approximately 15%.
[30]	Local calibration of saturation flow for multimodal traffic	Integrating locally derived saturation flow factors improved the predictive validity of intersection models in heterogeneous traffic conditions.
[26]	Roundabout–signal hybrid control systems	The hybrid control framework significantly decreased travel time and enhanced overall network operating efficiency.
[31]	Right-turn pocket design at four-leg intersections	Extending right-turn bay lengths effectively reduced approach delays by between 10% and 20%, contributing to smoother traffic flow.

3. METHODOLOGY

3.1 Description of the Study Area

The research was conducted in Ilorin, the capital city of Kwara State, Nigeria. Ilorin functions as a key regional hub connecting the northern and southern transportation corridors of the country. The city's road network comprises arterial and collector routes intersecting through a mix of roundabouts and signal-controlled junctions, which manage substantial volumes of commuter and freight traffic. These intersections are central to assessing overall network efficiency, congestion intensity, and safety performance.

The study focused on eleven (11) major intersections strategically distributed across key corridors of the Ilorin metropolis. The selected sites represent distinct geometric and control configurations: roundabouts, three-legged (T), and four-legged (+) intersections, to enable comparative analysis of performance variations. The details of the selected intersections are presented in Table 2.

Table 2: Locations and intersection types of selected urban roads in Ilorin metropolis

S/N	Location Junction	Intersection Type
1	Oja-Oba Pakata	Roundabout (O)
2	Offa Garage	Roundabout (O)
3	Tanke Junction	Four-legged (+)
4	Maraba Junction	Four-legged (+)
5	Gambari Junction	Three-legged (T)
6	Rheomich Junction	Three-legged (T)
7	Stadium Road Junction	Three-legged (T)
8	Royals Junction	Four-legged (+)
9	Ita Amodu Junction	Three-legged (T)
10	NYSC Secretariat	Four-legged (+)
11	Gaa-Akanbi	Roundabout (O)

This sampling ensured a balanced representation of geometric design, traffic control type, and spatial distribution, which are essential for conducting robust descriptive and inferential analyses.

3.2 Data Collection

The data collection process comprised two major components:

i. measurement of geometric characteristics, and
ii. traffic flow observation using video-based field surveys.

Both datasets were collected in accordance with established traffic engineering procedures.

3.2.1 Geometric characteristics

Geometric data capture the physical design attributes that influence an intersection's capacity, flow efficiency, and safety. The primary variables measured include lane width, number of approach lanes, turning radius, approach gradient, sight distance, and turn-bay or median lengths.

Measurements were conducted manually using steel tapes and calibrated rulers to ensure high accuracy, particularly suited for intersections of moderate scale. The field procedure involved physical demarcation of approach lanes, direct measurement of turning paths, and documentation of auxiliary geometric elements such as medians and channelization features.

3.2.2 Traffic flow data collection

Traffic flow data were recorded using digital video cameras positioned to capture all approach and turning movements at each intersection. Filming was conducted during the morning peak period (07:30–09:30 a.m.) for seven consecutive days. Recorded footage was later analysed manually to extract detailed vehicle counts, classified by type, direction, and movement pattern.

3.3 Data Analysis

Data analysis combined **descriptive** and **inferential** statistical techniques to evaluate intersection performance and determine the significance of differences among intersection types.

3.3.1 Descriptive/Operational analysis

Descriptive analysis involved computation of average delay, queue length, and Level of Service (LOS) for each intersection, based on [2] procedures.

i. Queue Length Estimation: $Q = Nq \times Lv$
ii. Delay Estimation: $D = (Texit - Tentry) - Tff$
iii. Level of Service (LOS):
Classified according to [2] thresholds:
LOS A (≤10 s), B (10–20 s), C (20–35 s), D (35–55 s), E (55–80 s), and F (>80 s).

3.3.2 Inferential/Statistical analysis

Inferential statistics were performed using IBM SPSS Statistics (Version 25) at a 95% confidence level ($\alpha = 0.05$).

i. One-way ANOVA was applied to test for significant differences in mean delay and queue length among roundabout, three-leg, and four-leg intersections.
ii. Tukey's HSD test was employed for post hoc pairwise comparisons.
iii. Multiple linear regression examined the effect of geometric and traffic variables on delay and queue length.
iv. Chi-square tests evaluated associations between categorical variables such as intersection type and LOS.

3.4 Summary of Analytical Framework

The adopted methodology integrates empirical field observations, direct measurement, and statistical modelling to assess intersection performance under heterogeneous traffic conditions. This approach ensures:

a) reliable quantification of operational metrics such as delay and queue length,
b) statistically valid differentiation across intersection types, and
c) evidence-based interpretation aligned with [2] standards.

4. RESULTS AND DISCUSSION

4.1 Operational Analysis of Intersection Performance

The operational performance of selected intersections within Ilorin metropolis was evaluated using three primary indicators: average queue length, control delay, and Level of Service (LOS). These measures were analyzed in accordance with the Highway Capacity Manual (HCM, 2022) standards, where LOS "A" represents free-flow operation (⩽10 s/veh) and LOS "F" denotes highly congested or oversaturated conditions (>80 s/veh).

Summary of the performance indices, revealing notable variability among intersection types. Several locations recorded mean delays exceeding 100 s/veh, confirming operational failure typical of saturated intersections.

Four-legged intersections exhibited substantial congestion, particularly at Tanke Junction and Maraba, which recorded average delays between 70–80 s and queue lengths of 80–86 m (LOS E). These conditions reflect operations near or beyond capacity, characterized by unstable queues and repetitive stop–go cycles. Conversely, the NYSC Secretariat intersection demonstrated moderate efficiency (delay = 55 s; LOS D), attributed to lower approach volumes and intermittent manual traffic control that occasionally mitigated queuing.

Three-legged (T-type) intersections, including Roemich, Taiwo, Ita-Amodu, Gambari, and Balogun Fulani, performed the poorest, with mean delays ranging from 90–134 s and queues extending 98–140 m, corresponding to LOS F. Despite having fewer conflict points, their inefficiency was largely due to poor control measures, inconsistent right-of-way enforcement, and blockages caused by dominant major-road traffic streams.

Roundabouts, on the other hand, displayed comparatively better performance, confirming their superior operational efficiency under balanced traffic conditions. Gaa-Akanbi Roundabout achieved a delay of 35 s (LOS C), indicating stable flow. Oja-Oba and Offa Garage roundabouts

recorded LOS D and E respectively, influenced primarily by pedestrian interference and excessive circulating flow rates (>1,100 veh/h).

4.2 Traffic Flow Characteristics

Traffic volume analysis revealed a strong positive association between vehicular demand and delay, although geometry and control features significantly moderated the overall performance. Among the three-legged intersections, Ita-Amodu carried the highest traffic volume (882 veh/h) and experienced the most severe congestion (LOS F). Similarly, Taiwo and Sobi intersections, despite moderate volumes, exhibited high delays due to geometric deficiencies such as narrow lanes and inadequate storage capacity.

4.3 Inferential Statistical Analysis

Inferential statistical tests were conducted to determine whether observed operational differences among intersection types were statistically significant. Analytical methods included one-way ANOVA, Tukey's post hoc test, independent t-tests, multiple regression, and chi-square tests.

The ANOVA results revealed significant variation in both mean delay and queue length across intersection types ($F_delay = 40.071$, $p < 0.001$; $F_queue = 28.921$, $p < 0.001$). These outcomes confirm that intersection geometry and control configuration significantly influence vehicular delay and queuing.

Tukey's HSD test further clarified the magnitude of differences: roundabouts performed significantly better than both three-leg and four-leg intersections for delay and queue metrics ($p < 0.01$), with mean differences of −97.8 s (delay) and −75.1 m (queue) compared to three-legged intersections.

Regression analysis quantified the relative contributions of key variables. The model explained 92.7% of the variance in delay ($R^2 = 0.927$, $p = 0.0002$). Intersection type emerged as the strongest predictor, roundabouts reduced delay by approximately 102 s ($p < 0.001$), and four-legged intersections by 45 s ($p = 0.005$) relative to three-legged intersections.

Across all analytical frameworks, a consistent performance hierarchy emerged: Roundabouts > Four-legged intersections > Three-legged intersections.

The convergence of ANOVA, Tukey, and t-test outcomes reinforces this hierarchy, while regression results highlight intersection geometry as the dominant factor shaping operational outcomes. These findings collectively demonstrate that geometric design and control mechanisms are more decisive determinants of efficiency than traffic volume alone.

5. CONCLUSION

This study comprehensively assessed the operational performance of urban intersections in Ilorin, elucidating the complex interrelationship among traffic demand, intersection geometry, and control strategies. Results reveal that intersection performance is predominantly influenced by geometric and operational characteristics rather than volume alone. Four-legged intersections exhibited sustained congestion (LOS E), primarily due to high approach volumes, multiple conflict points, and inefficient control systems. Three-legged intersections performed worst (LOS F), reflecting inadequate control, poor right-of-way discipline, and geometric imbalance. Conversely, roundabouts demonstrated superior resilience and operational stability (LOS D–E), benefiting from balanced flows, sufficient circulatory width, and effective entry geometry. These results align with the [2] performance classifications and corroborate international findings that geometric deficiencies and suboptimal control strategies are as critical as traffic intensity in determining intersection performance. Statistical analyses (ANOVA, Tukey, t-tests) consistently confirmed that roundabouts achieved significantly lower delays and queue lengths than other intersection forms, while regression analysis underscored geometry as the primary determinant of performance. Although the chi-square test indicated a categorical association between intersection type and LOS, its inferential strength was limited by sample size. Overall, findings substantiate the hypothesis that intersection type and control design are central to operational efficiency. Roundabouts emerge as the most sustainable intersection form for current traffic conditions, while the persistent inefficiency of three-legged intersections underscores the need for geometric redesign and improved control management.

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