**Analysis of Signalized Traffic Control Systems in Uyo Metropolis**

**Abstract**

In Nigeria's largest cities, particularly in Uyo metropolis, traffic congestion is a critical issue. This paper examines the delays in traffic flow at sixteen signalized intersections in the metropolis for over three days during peak hours. Traffic data were extracted from aerial videos for each signalized intersection using drones. Performance indicators were computed to evaluate traffic characteristics. The Akçelik time-dependent model was used to determine the delay for under-saturated and over-saturated traffic conditions as well the uniform, random, and overflow components of delays and queues at all signalized junctions. This overcomes the limitations of existing works which implemented models that do not account for the effects of variable traffic demand and time periods of analysis, and considered three and eight intersections only. Findings show that the intersections that suffer continuous oversaturation for any day during these peak hours have overall average delay values of 814 and 1216 seconds respectively, and the highest average delay value of 1822 seconds was experienced at the intersection of Oron Road and Udo Umana Street. These values are significant to the efficiency of key major roads in the city, and they indicate a crucial metric in transportation engineering through which traffic engineers are able to optimize signal timings at intersections and implement various traffic management approaches to reduce congestion and enhance traffic flow.

**Keywords**: Delay estimation; signalized intersection; traffic flow; traffic lights.

**1. INTRODUCTION**

 A major problem in urban areas is traffic congestion that affects travel times of vehicles. It comes along with noise and air pollution, as well as high fuel consumption costs associated with the burning of fuels from stationary vehicles, and thus has a negative effect on the environment. [1] highlighted the role of road transport in Nigeria's cities as a contributing factor to ecological deterioration. Consequently, the socioeconomic development of the affected areas has been hampered, resulting in reduced working hours and thus productivity [2]. Traditional cities such as Lagos, Ibadan, Benin City, Port Harcourt, Abuja, Kano and Kaduna are not the only ones affected. Today, the problem of traffic congestion is faced by almost every state capital city in Nigeria. An effective way of confronting this problem is by using the queuing model to analyse the flow of traffic to and through an intersection controlled by traffic signals. This is accomplished by analysing the cumulative passage of vehicles as a function of time [3].

 Traffic behaviour at signalized and unsignalized intersections can be described using queuing theory [4; 5; 6]. According to [7], the two primary types of traffic flows are: uninterrupted flows and interrupted flows. Uninterrupted flows are all the flows regulated by vehicle-vehicle interactions and interactions between vehicles and the roadways, whereas interrupted flows are the flows regulated by external means such as traffic signals, and vehicle-vehicle and vehicle-roadways interactions. The interrupted traffic flows are considered for this research and the queuing theory model is adopted.

 Queues occur whenever demand at a specific point of time exceeds the capacity to provide a service, and queuing theory defines the mathematical study of these waiting lines [8]. Three basic elements form the basis for a common queuing system: the users’ arrival process in the system, the order in which the users are granted access to the service facility once they join the queue, and the service process, and departure from the system. According to [9], the arrival of customers, in a majority of queues, is entirely in a random fashion. This means that the length of time that has elapsed since the last occurrence of an event (arrival of customers or completion of service) does not influence the occurrence of the next event. The customers are produced according to a statistical distribution and their inter-arrival times are described by the distribution.

 The theory of traffic signals gives attention to the estimation of delays and the length of queues that result from the implementation of the signal control strategy at individual intersections and the sequence of intersections. Delays and queue lengths are the principal parameters that govern the determination of the effectiveness of intersection level of service (LOS), in assessing the adequacy of lane length and in estimating fuel consumption and emissions [10].

 [11] defined vehicle delay at a signalized intersection as the difference in travel time between vehicles not affected by a controlled intersection and those affected. The first theoretical delay method for signalized intersections was proposed with the deterministic arrival assumptions at the 7th Highway Research Board HRB) annual meeting in 1923. Ever since then, delay estimation methods have evolved continuously for almost 90 years in order to provide an improved model that aligns with real world delays for generalized traffic conditions [12].

 The stochastic and deterministic components of delay are the two components of delay that estimates the delay experienced by vehicles [10]. The stochastic component of delay is based on the steady-state queuing theory which describes the traffic arrival and service time distributions while the deterministic component of traffic delay is based on the fluid theory of traffic in which traffic stream is treated as a continuous fluid, and traffic demand and service are considered as continuous variables where flow rates vary over the time and space domain. It is estimated based on the following assumptions: at the start of the green phase there is a zero initial queue; at the arrival flow rate, there is a uniform arrival pattern over the entire cycle; at the saturation flow rate, there is a uniform departure pattern when a queue is present, and at the arrival flow rate when the queue disappears; and arrivals do not exceed the signal capacity.

 Delay can be estimated by field measurement, simulation, and analytical models. According to [13], the analytical model is the most practical and convenient method, and a number of these models have been proposed and developed on the basis of different assumptions for various traffic conditions. [14] stated that in analytical models, delay time can be classified as deterministic, steady state or time-dependent model respectively in accordance with the entrance or exit characteristics of traffic flows.

 [13] opined that the stochastic steady-state delay models are applicable for under-saturated conditions and use the assumptions that arrivals are random and departure headways are uniform, but these models predict infinite delay when arrival flows approach capacity. Deterministic models predict more realistic traffic delay for over-saturated conditions, but these models do not take into account the effect of randomness in traffic flow. The steady state model assumptions are broken when the traffic flow rate is approaching or exceeding the capacity, at least for a given period of time, because it cannot achieve an equilibrium stochastic condition. There is an increased likelihood of cycle failure as traffic intensity increases, where some cycles will start facing a random overflow queue of the vehicles that could not be released from a previous cycle. This additional delay caused by the effect of the presence of an initial queue can be accounted for using the delay models based on queuing theory and the *M/D/n/*FIFO queuing system summarizes queuing system at the signalized intersection. At extremely congested conditions, the deterministic models are used, for they are appropriate for highly oversaturated signalized intersections.

 The basic deterministic delay model assumes a constant arrival process that persists for a time interval of length, t, and at the start of the cycle, the queue is zero [15]. The deterministic model is used to estimate delay at the signalized intersections when the arrival flow rate exceeds the capacity of the system. Time-dependent models incorporate both deterministic (uniform) and stochastic components of traffic conditions [10]. They were adopted in view of the need to improve the estimation of traffic performance for under-saturated and oversaturated conditions, and to fill in the gap in delay models that are applicable to the range of traffic flows that are close (numerically) to the signal capacity. They give more realistic estimations of traffic delay at signalized intersections and are a combination of the steady state and deterministic model. Akçelik time-dependent model is obtained from the coordinate transformation technique [15]. The transformation technique provides an expression for overflow delay and derives a transition function for the average overflow queue. This function relates the steady state function for undersaturated signals to deterministic function for continuous saturated signals, yielding realistic finite values, while incorporating a random element into the deterministic oversaturation function.

 One of the problems facing the transportation in Uyo metropolis is a lack of an effective and efficient estimator of total traffic delay at the different signalized intersections during the peak hours, morning (7 am to 10 am) and evening (5 pm to 8 pm) respectively. In this research paper, a traffic flow analysis is considered for sixteen signalized intersections in Uyo metropolis to determine the average vehicular delay at each intersection during the morning and evening peak hours. The selected signalized intersections are identified on the road network and the traffic flow data is collected and analysed using the time-dependent delay model. Thus, the aim of the research work is to critically examine the vehicular delays at signalized intersections in the metropolis during peak hours to help lessen traffic congestion. This can be achieved via the following processes: identifying the road network and all signalized intersections in the road network, collecting and organizing the traffic flow data at each signalized intersections, and conducting a full network-wide analysis of the traffic flow data using an effective and efficient estimator to give more realistic estimations of traffic delay.

Previous works focused on three signalized intersections and eight unsignalized congestion-prone intersections without consideration to a full network-wide analysis. This study extends existing studies in the literature, which mainly focused on using models that are not very useful in practice in estimating traffic conditions.

 This research paper is organized as follows. Section 2 presents the description of the study area and the methods adopted for traffic data collection and analysis at signalized intersections. Section 3 presents an interpretation of the results obtained from the analysis and the relationship established between the variables. Section 4 deeply discusses on the implication of the result of the experimental data. Section 5 presents a summary of the research results, the limitations of the study and proposes topics for future research.

**2. MATERIALS AND METHODS**

**2.1 Study Area**

Uyo is the capital of Akwa Ibom state, south-south Nigeria. It is located at Latitudes 4° 58′ and 5° 05′ N and Longitudes 7° 54′ and 8° 00′ E (see Fig..1). The city lies within the tropical rain forest and shares boundary in the north with Ikono, Itu and Ibiono Ibom Local Government Areas (LGA), in the East with Uruan LGA, in the west with Abak and in the south with Ibesikpo Asutan and Nsit Ibom LGA [16]. According to [17], the city has a mean annual temperature between 22.81 °C and 30.13 °C, an annual rainfall averages between 1800 mm and 3200 mm and enjoys a wet season and a dry season from March to October and November to February correspondingly.

 Data was obtained from the selected sixteen signalized intersections in Uyo metropolis in Nigeria which form the road network. The fixed traffic light labels, location of fixed traffic light and the corresponding direction of traffic flow are presented in Table 1. The names of selected junctions and their respective labels are provided in Table 2. [18] presents Appendices C and E that show the number of vehicle arrivals during both peak hours

 **Table 1: Traffic light ID and location (Field data)**

|  |  |  |
| --- | --- | --- |
|  Traffic Light ID | Location of Traffic Light | Direction of Traffic Flow |
| T1 | Abak Road by Ukana Offot Street | J1 – J5  |
| T2 | Abak Road by Udo Uweme Street | J4 – J5 |
| T3 | Abak Road by Udo Eduok | J5 – J4 |
| T4 | Abak Road.by Udo Obio | J3 – J4 |
| T5 | Oron Road by Gibbs Street | J6 – J7 |
| T6 | Oron Road by Udo Umana Street | J8 – J7 |
| T7 | Oron Road by Udo Umana | J9 – J7 |
| T8 | Oron Road by Udotung Ubo | J6 – J12 |
| T9 | Oron Road by Udosen Uko Street | J12 – J6 |
| T10 | Oron Road by Zenith Bank | J12 – J13 |
| T11 | Oron Road by May Flower | J13 –J12  |
| T12 | Oron Road by Nsikak Eduak Avenue | J12 – J13 |
| T13 | General Edet Akpan Avenue by Oron Road | J14 – J13 |
| T14 | Nsikak Eduok Avenue by Oron Road | J2 – J13 |
| T15 | Udo Umana Street by Aka Itiam Street | J9 – J10 |
| T16 | Aka Itiam Street by Udo Umana Street | J11 – J10 |

**Table 2: Names of selected junction (Field data)**

|  |  |
| --- | --- |
|  Junction Label | Name of Junction |
| J1 | Secretariat Junction |
| J2 | Aka Rd./IBB Junction |
| J3 | Abak Rd. Plaza ByPass Junction |
| J4 | Abak Rd./Udo Obio/Udo Eduok Junction |
| J5 | Abak Rd./Ukana Offot Junction |
| J6 | Oron Rd./Nwaniba Junction |
| J7 | Oron Rd. /Udo Umana/Gibbs street Junction |
| J8 | Oron Rd. Plaza ByPass Junction |
| J9 | Udo Umana/Obio Imo Junction |
| J10 | Aka Itiam/Udo Umana Junction |
| J11 | 2lane/Aka Itiam Junction |
| J12 | Oron Rd/Obio Imo Junction |
| J13 | Oron Rd/2lane/4lane Junction |
| J14 | 4lane/Nwaniba water fountain Junction |

**2.2 Data Collection**

 Data were extracted from aerial videos considered for each selected fixed traffic-light intersection, and manual counting was used to count the number of vehicles. The data considered for this study were the number of vehicles arriving at the queue for a period of three hours, the number of vehicles leaving the queue during the green time for a period of three hours and the number of vehicles in the queue at the start of traffic light cycle, effective green light time, effective red light time and cycle time. The traffic data was collected simultaneously during the morning and evening traffic peak period (7 am to 10 am and 4 pm to 7 pm respectively) for a period of three days (Monday to Wednesday). A schematic diagram of the studied environment and the selected road network is shown in Fig. 1 and 2.



 **Fig..1 Map of Akwa Ibom State highlighting Uyo Local Government Area**



**Fig..2 Map of the selected road network**

**2.3 DATA ANALYSIS**

The process was modelled using the {*(M/D/1): (∞/FCFS)*} queuing model with the following assumption

1. The arrival flow rate, (q), for the arrival of vehicles is a Poisson distribution, since vehicular arrival is random.
2. There is a fixed-cycle regulation at the intersection.
3. There is a constant interval between departures of vehicles.
4. There is only one server in each of the routes, which occasionally goes on a break to serve clients from a different route.
5. The service capacity is not limited.
6. The service policy is non-stimulated constant time with customers served under a First-come-first-served system.

**Basic Notations**

c: Cycle length (sec)

g: Effective green time (sec)

*At*: Maximum queue length (number of arrivals during cycle time)

tm: Number of arrivals measured time (sec)

*r*: Effective red time (sec)

*Dt* : Maximum number of departure during green time, g

Δ*Dt:* Reserved capacity in cycle (Non-delayed arrivals)

Q*0*: Expected overflow queue length (veh) [The overflow queue from previous cycle]

*q*: Arrival flow rate of vehicle per second during red light

*S*: Saturation flow rate of vehicle per second during green light

*μ*: Service rate of vehicle per time length of green time, g

Q: Capacity in vehicles per hour (sec)

Q(0): Vehicle queue length at the beginning of a cycle

Q(c): Vehicle queue length at the end of a cycle

*Y*: Flow ratio

*X*: Degree of saturation

AWT: Average waiting time

The time dependent model by [15] for the {*(M/D/1) : (∞/FCFS)*} queuing model was employed.

Let

 Q(c) = Q(0) + *At*  - *Dt* + ∆*Dt*  Equation 2.1

where ∆*Dt* = {*Dt* - Q(0) - *At* , if Q(0) + *At* < *Dt* , zero otherwise}.

If the system is in equilibrium, then,

 Q(0) = Q(c) Equation 2.2

Also,

 Equation 2.3

 Equation 2.4

  Equation 2.5

 Equation 2.6

 Equation 2.7

  Equation 2.8

The queue is in equilibrium if

The delay (average waiting time – AWT) of vehicles per cycle for the steady state model applicable for under-saturated traffic conditions is given as

 Equation 2.9

where Q0 is [19] expression for the overflow queue formula under Poisson arrival and fixed service time during green time, and it is given as

 Equation 2.10

AWT is the sum of two delay terms: D = Du + Dr, where Du is the first term in Equation 2.9 that represents the uniform delay term, where arrival rate is less than the capacity of the system, while Dr is the second term in Equation 2.9 that represents the random overflow delay term caused by temporary random overflow of higher than capacity flow rates.

The time-dependent model was adopted to calculate the average overall delay during the observation interval (0, T) as follows:

 *D = Du + Do*

where *Du* = uniform delay term and Do is the sum of random and oversaturated flow delays that represents the overflow delay term for oversaturated flow conditions. For under-saturated conditions (X<1), Du is represented by the first term in Equation 2.9, while Du is given the first term in the deterministic expression for oversaturated conditions.

The traffic data collected was analysed using the Akçelik time dependent model given as

 Equation 2.11

where Equation 2.12

 Equation 2.13

Du is the uniform delay term and the second term is the deterministic overflow delay term for oversaturated conditions.

Akçelik’s time dependent transition function for the average overflow queue during the time interval [0, T] was adopted given as

 Equation 2.14

where and T = specified time of analysis

**2.3.1 Analysis of Performance Measures**

**i. Arrival Flow Rate**

Equation 2.3 was used to compute the arrival flow rate, q, for the morning and evening peak hours and presented in Appendix Gfor the morning session and Appendix Hfor the evening session [18].

**ii. Saturation Flow Rate**

Equation 2.4 was used to compute the saturation flow rate, , measured in units of vehicles per second and presented in Appendix G and Appendix Hfor the morning and evening session respectively [18].

**iii. Service Rate (*μ*) and Traffic Flow Ratio (*Y)* (Traffic Intensity)**

 Equation 2.5 and Equation 2.6 were used to calculate the service rate of vehicle per length of green time (μ) and the traffic flow ratio (*Y*). The service rate of vehicle per length of green time and the traffic flow ratio for the morning and evening peak hours were calculated and the results are contained within Appendix G for the morning session and Appendix H for the evening session.

**iv. Green Time/Cycle Time Ratio (λ) and Degree of Saturation (*X)***

Equation 2.7 was used on the green time and cycle time data contained in Appendix D and Appendix C for the morning peak hours and Appendix F and Appendix E for the evening peak hour to obtain the green time/cycle time ratio, λ, for both peak hours. These are contained within Appendix G and Appendix H correspondingly {18].

 Equation 2.8 was engaged to obtain the degree of saturation for the morning and evening peak hours and the results are shown within Appendix Gfor the morning session and Appendix H for the evening session [18].

**v. Average Total Delay for Under-saturated Traffic Conditions**

 Equation 2.11 was employed to calculate the average delay of vehicles for the under-saturated traffic situations where x < 1.

Employing Equation 2.12, Equation 2.13, Equation 2.14 and Equation 2.15 for x < 1 on Appendix I and Appendix J, the average delay of vehicles in seconds for the morning and evening peak hours are computed and the results shown in Appendix K and Appendix L respectively [18].

**vi. Average Total Delay in Over-saturated Traffic Condition**

 Equation 2.11 was adopted to obtain the average delay per vehicle for the oversaturated traffic situation for traffic flow rate greater than capacity rate where x ≥ 1.

Equation 2.12, Equation 2.13, Equation 2.14 and Equation 2.15 for x ≥ 1 were applied to Appendix I and Appendix J, and the average delay per vehicle in seconds for the morning and evening peak hours are computed and the results are presented in Appendix K and Appendix L respectively [18].

**3. RESULTS**

 Sixteen signalized intersections were analysed to find the vehicular delay at each fixed-time traffic light during peak hours (morning and evening) for three days, and to carry out a comparative analysis between delays experienced during these peak hours.

 During the morning peak hours for day 1, day 2 and day 3, T1, T2, T3, T4, T8 and T9 experience a cycle length of 112 seconds, T5, T6 and T7 experience a cycle length of 179 seconds, T10 and T11 experience a cycle length of 124 seconds, T12, T13 and T14 experience a cycle length of 165 seconds, and T15 and T16 experience a cycle length of 108 seconds. See Appendix C [18].

 Similarly, during the evening peak hours for day 1, day 2 and day3, T3, T4, T8 and T9 experience a cycle length of 112 seconds, T5, T6 and T7 experience a cycle length of 179 seconds, T10 and T11 experience a cycle length of 124 seconds, and T15 and T16 experience a cycle length of 108 seconds, T12, T13 and T14 experience a cycle length of 175 seconds, which is a cycle length difference of 10 seconds between the morning and evening peak hours, and T1 and T2 experience a cycle length of 156 seconds, which is a cycle length difference of 44 seconds between the morning and evening peak hours. See Appendix E [18].

 The effective green-time for T3, T4, T5, T6, T7, T8, T9, T10, T11, T15 and T16 during both peak hours is same for day 1, day 2 and day 3. Both T1 and T2 have a green time of 31 seconds for the morning peak hours and a green time of 42 seconds during the evening peak hours for day 1, day 2 and day 3. There is a difference of 10 seconds in green time for T12, T13 and T14 between the morning and evening peak hours for day 1, day 2 and day 3, where the green time in seconds for the evening peak hours is higher. See Appendix D and F [18].

 The results of analysed traffic light data presented in Appendix G show that T4, T5, T6, T7 and T9 have a degree of saturation (X) greater than 1 (X >1) during the morning traffic peak hours for day 1, day 2 and day 3, where X = 1 at T4 for day 1, while T3 and T12 have X=1 for day 2. Similarly, for the evening peak hours, T3, T4, T5, T7 and T15 have X>1 for day 1, day 2 and day 3, including X=1 at T14 for day 1 only and X=1 at T1 for day 2 and day 3 as shown in Appendix H [18].

 Appendices C and D present the number of vehicle arrivals during cycle time (*At*) and maximum vehicle departure during green time (Dt) for the morning peak hours, while Appendices E and F show similar data collected for the evening peak hours. It is revealed that T4, T5, T6, T7 and T9 have *At* ≥ Dt, for day 1, day 2 and day 3 during the morning peak hours, where *At* = Dt at T4 for day 1. Likewise, during the evening peak hours, T3, T4, T5, T7, T15 have *At* > Dt, for day 1, day 2 and day 3, and *At* = Dt at T14, for day 1 and day 3 respectively [18].

 The flow ratio and green time/cycle time ratio during both peak hours for each traffic light is presented in Appendices G and H [18]. It is seen that during the morning peak hours, T4, T5, T6, T7, and T9 have flow ratio, *Y*, greater than their corresponding green time/cycle time ratio, λ, (*Y* > λ), for day 1, day 2, and day 3, excluding T4 for day 1, where *Y* = λ. T3 and T12 have *Y* = λ for day 2. Similarly, during the evening peak hours, T3, T4, T5, T7 and T15 have *Y* > λ for day 1, day 2 and day 3, T1 has *Y* = λ for day 2 and day 3, and T14 has *Y* = λ for day 1.

Fig. 3. to 8 compare the result of the vehicle flow ratio and green time/cycle time ratio during both peak hours for day 1, day 2 and day 3.

**Fig. 6 Flow Ratio versus Green Time/Cycle Time**

 **Ratio (Evening - Day 1)**

**Fig. 3 Flow Ratio versus Green Time/Cycle**

 **Time Ratio (Morning - Day 1)**

**Fig. 7 Flow Ratio versus Green Time/Cycle Time**

 **Ratio (Evening - Day 2)**

 **Fig. 4 Flow Ratio versus Green Time/Cycle Time Ratio**

**(Morning - Day 2)**

**Fig. 8 Flow Ratio versus Green Time/Cycle Time**

 **Ratio (Evening - Day 3)**

**Fig. 5 Flow Ratio versus Green Time/Cycle Time**

 **Ratio (Morning - Day 3)**

 Appendices I and J present the uniform and overflow delay in seconds for each traffic light during the morning and evening peak hours for day 1, day 2 and day 3 [18]. It is observed that for traffic lights T4, T5, T6, T7 and T9, each attains the same maximum uniform vehicle delay during the morning peak hours for day 1, day 2 and day 3, including T3 and T12, where maximum uniform delay is attained in day 2. Similarly, during the evening peak hours, T3, T4, T5, T7 and T15 attain the same maximum uniform vehicle delay for day 1, day 2 and day 3, including T1, which attains maximum uniform delay for day 2 and day 3, and T14 for day 1.

 The overall highest value for overflow delay component in seconds is experienced at T9 in day 3 and the overall lowest value for overflow delay component in seconds is experienced at T13 in day 1 during the morning peak hours. Furthermore, the highest value for overflow delay component in seconds is encountered at T9 for day 1 and T5 for day 2, while the lowest value for overflow delay component for day 2 and day 3 is encountered at T13. T13 experiences the lowest value of overflow delay component in seconds for day 1, day 2 and day 3. See Appendix I [18].

 Likewise, during the evening peak hours, the overall highest value for overflow delay component in second is faced at T7 in day 1, while the overall lowest value for overflow delay component in seconds is experienced at T13 in day 1. Also, the highest value for overflow delay component for day 2 and day 3 is experienced at T7, while the lowest value for overflow delay component for day 2 and day 3 is experienced at T16, J11 – J10 direction of flow. T7 experiences the highest value for overflow delay component in seconds for day 1, day 2 and day 3. See Appendix J [18].

 Appendix K and L present the average total delay for both peak hours. It is revealed that for the morning peak hours, the overall highest delay is seen at T9, J12 – J6 direction of flow, in day 3, while the overall lowest delay is seen at T16, J11 – J10 direction of flow, in day 1. Furthermore, the highest delay for day 1 and day 2 is experienced at T5, J6 – J7 direction of flow. Whereas the lowest vehicle delay for day 2 and day 3 is experienced at T16, J11 – J10 direction of flow [18].

 The overall highest delay during the evening peak hours is faced at T7, J9 – J7 direction of flow, in day 1 and the overall lowest vehicle delay is faced at T16, J11 – J10 direction of flow, in day 3. Likewise, the highest vehicle delay for day 2 and day 3 is experienced at T7, J9 – J7 direction of flow and the lowest delay is encountered at T16, J11 – J10, for day 1, day 2. Consequently, the highest traffic delay is encountered at T7, intersection of Oron Road and Udo Umana Street (J9 – J7 direction of flow) and the lowest traffic delay is encountered at T16, intersection of Aka Itiam Street and Udo Umana Street (J11 – J10 direction of flow) during the evening peak hours for day 1, day 2 and day 3. See Appendix L [18].

 The morning peak hours total delay in seconds for both traffic conditions (under-saturated and over-saturated) is presented in Table 3., while the evening peak hours total delay in seconds is presented in Table 4 for both traffic conditions. As seen in Table 3., T5 experiences the highest continuous delay during the morning peak hours for day 1 and day 2, and T9 experience the highest continuous delay for day 3. Continuous overflow delay refers to the delay faced by vehicles that cannot discharge during the signal cycle because the arrival flow rate exceeds the capacity of the traffic queueing system. T16 experiences the lowest total delay throughout the morning peak hours for all three days. Consequently, it is shown in Table 4 that T7 and T16 experience the highest continuous delay and the lowest total delay during the evening peak hours for all three days respectively.

 **Table 3: Average total delay (Field data)**

|  |
| --- |
| Morning |
| Traffic Light ID | **Direction of Road Segment** | **Total Delay (sec)** |
| **Day 1** | **Day 2** | **Day 3** |
| T1 | J1 – J5  | 48.02 | 47.82 | 48.02 |
| T2 | J4 – J5 | 39.03 | 39.00 | 39.03 |
| T3 | J5 – J4 | 51.83 | 121.89 | 63.92 |
| T4 | J3 – J4 | 118.07 | 284.19 | 286.53 |
| T5 | J6 – J7 | 1102.20 | 1263.37 | 1101.84 |
| T6 | J8 – J7 | 674.50 | 887.80 | 1263.37 |
| T7 | J9 – J7 | 710.50 | 516.67 | 710.50 |
| T8 | J6 – J12 | 53.76 | 53.29 | 44.82 |
| T9 | J12 – J6 | 1076.08 | 915.31 | 1290.92 |
| T10 | J12 – J13 | 41.04 | 41.04 | 39.31 |
| T11 | J13 – J12  | 39.31 | 43.37 | 41.04 |
| T12 | J12 – J13 | 90.13 | 160.17 | 90.13 |
| T13 | J14 – J13 | 54.13 | 55.26 | 54.91 |
| T14 | J2 – J13 | 61.28 | 66.63 | 64.04 |
| T15 | J9 – J10 | 32.72 | 38.24 | 38.87 |
| T16 | J11 – J10 | 31.15 | 31.22 | 31.22 |

\* Traffic data shown in Appendices [18]

**Table 4: Average total delay (Field data, 2023)**

|  |
| --- |
| Evening |
| Traffic Light ID | **Direction of Road Segment** | **Total Delay (sec)** |
| **Day 1** | **Day 2** | **Day 3** |
| T1 | J1 – J5  | 75.74 | 131.51 | 132.62 |
| T2 | J4 – J5 | 60.04 | 56.52 | 56.68 |
| T3 | J5 – J4 | 652.93 | 652.29 | 651.73 |
| T4 | J3 – J4 | 1025.53 | 1187.31 | 1401.36 |
| T5 | J6 – J7 | 1693.97 | 1855.60 | 1693.97 |
| T6 | J8 – J7 | 75.46 | 86.35 | 75.46 |
| T7 | J9 – J7 | 1878.22 | 1872.64 | 1714.50 |
| T8 | J6 – J12 | 39.37 | 53.29 | 33.90 |
| T9 | J12 – J6 | 53.76 | 67.95 | 69.54 |
| T10 | J12 – J13 | 46.86 | 52.07 | 52.07 |
| T11 | J13 – J12  | 41.04 | 43.51 | 41.04 |
| T12 | J12 – J13 | 97.02 | 97.02 | 98.26 |
| T13 | J14 – J13 | 55.64 | 60.92 | 57.23 |
| T14 | J2 – J13 | 185.56 | 116.27 | 116.27 |
| T15 | J9 – J10 | 545.02 | 702.90 | 705.07 |
| T16 | J11 – J10 | 37.62 | 33.69 | 32.89 |

\* Traffic data shown in Appendices [18]

 The comparison of the result of the analysis of vehicular delay at each fixed-timed signalized intersection for the morning and evening peak hours is presented graphically in Fig. 9 and 10. The blue, red and green bars represent day 1, day2 and day 3 respectively. The total delay obtained from the analysis represents the accumulated time in seconds for each signalized intersection.

**Fig. 9 Average total delay – morning peak hours**

**Fig. 10Average total delay – evening peak hours**

The flow ratio, *Y* and green time/cycle time ratio, λ, for the morning and evening peak hours for day 1, day 2 and day 3 are presented in Table 5 and 6

 **Table 5: Flow ratio and green time/cycle time ratio - morning peak hours (Field data)**

|  |  |  |  |
| --- | --- | --- | --- |
| Traffic LightID | Day 1 | Day 2 | Day 3 |
| **Flow Ratio (*Y*)** | **Green Time/Cycle Time Ratio (λ)** | **Flow Ratio (*Y*)** | **Green Time/Cycle Time Ratio (λ)** | **Flow Ratio (*Y*)** | **Green Time/Cycle Time Ratio (λ)** |
| T1 | 0.26 | 0.28 | 0.26 | 0.28 | 0.26 | 0.28 |
| T2 | 0.23 | 0.28 | 0.23 | 0.28 | 0.23 | 0.28 |
| T3 | 0.26 | 0.28 | 0.28 | 0.28 | 0.27 | 0.28 |
| T4 | 0.28 | 0.28 | 0.29 | 0.28 | 0.29 | 0.28 |
| T5 | 0.32 | 0.27 | 0.33 | 0.27 | 0.32 | 0.27 |
| T6 | 0.30 | 0.27 | 0.31 | 0.27 | 0.33 | 0.27 |
| T7 | 0.30 | 0.27 | 0.29 | 0.27 | 0.3 | 0.27 |
| T8 | 0.29 | 0.31 | 0.29 | 0.31 | 0.28 | 0.31 |
| T9 | 0.37 | 0.31 | 0.36 | 0.31 | 0.38 | 0.31 |
| T10 | 0.29 | 0.34 | 0.29 | 0.34 | 0.28 | 0.34 |
| T11 | 0.28 | 0.34 | 0.3 | 0.34 | 0.29 | 0.34 |
| T12 | 0.18 | 0.19 | 0.19 | 0.19 | 0.18 | 0.19 |
| T13 | 0.08 | 0.19 | 0.09 | 0.19 | 0.09 | 0.19 |
| T14 | 0.13 | 0.19 | 0.15 | 0.19 | 0.14 | 0.19 |
| T15 | 0.26 | 0.34 | 0.29 | 0.34 | 0.29 | 0.34 |
| T16 | 0.12 | 0.25 | 0.12 | 0.25 | 0.12 | 0.25 |

\* Traffic data shown in [18]

**Table 6: Flow ratio and green time/cycle time ratio – evening peak hours (Field data)**

|  |  |  |  |
| --- | --- | --- | --- |
| Traffic LightID | Day 1 | Day 2 | Day 3 |
| **Flow Ratio (*Y*)** | **Green Time/Cycle Time Ratio (λ)** | **Flow Ratio (*Y*)** | **Green Time/Cycle Time Ratio (λ)** | **Flow Ratio (*Y*)** | **Green Time/Cycle Time Ratio (λ)** |
| T1 | 0.26 | 0.27 | 0.27 | 0.27 | 0.27 | 0.27 |
| T2 | 0.24 | 0.27 | 0.23 | 0.27 | 0.23 | 0.27 |
| T3 | 0.31 | 0.28 | 0.31 | 0.28 | 0.31 | 0.28 |
| T4 | 0.33 | 0.28 | 0.34 | 0.28 | 0.35 | 0.28 |
| T5 | 0.35 | 0.27 | 0.36 | 0.27 | 0.35 | 0.27 |
| T6 | 0.25 | 0.27 | 0.26 | 0.27 | 0.25 | 0.27 |
| T7 | 0.36 | 0.27 | 0.36 | 0.27 | 0.35 | 0.27 |
| T8 | 0.26 | 0.31 | 0.29 | 0.31 | 0.22 | 0.31 |
| T9 | 0.29 | 0.31 | 0.3 | 0.31 | 0.3 | 0.31 |
| T10 | 0.31 | 0.34 | 0.32 | 0.34 | 0.32 | 0.34 |
| T11 | 0.29 | 0.34 | 0.3 | 0.34 | 0.29 | 0.34 |
| T12 | 0.23 | 0.24 | 0.23 | 0.24 | 0.23 | 0.24 |
| T13 | 0.14 | 0.24 | 0.17 | 0.24 | 0.15 | 0.24 |
| T14 | 0.24 | 0.24 | 0.23 | 0.24 | 0.23 | 0.24 |
| T15 | 0.37 | 0.34 | 0.38 | 0.34 | 0.38 | 0.34 |
| T16 | 0.18 | 0.25 | 0.15 | 0.25 | 0.14 | 0.25 |

\* Traffic data shown in [18]

The correlation technique is used on Tables 5 and 6 to obtain the correlation coefficient, r, between the flow ratio and green time/cycle time ratio for day 1, 2 and day 3 during peak periods. The coefficient reveals the extent of relationship between flow ratio and green time/cycle time ratio. The correlation coefficient is calculated using the Pearson’s correlation coefficient which is given by

 where x = flow ratio *Y*, and y = green time/cycle time ratio, λ*.*

Table 7 shows the Pearson correlation between the flow ratio and corresponding green time/cycle time ratio for the morning and evening peak hours for day 1, day 2 and day 3.

**Table 7: Correlation coefficient between flow ratio and green time/cycle**

**time ratio for selected days during both peak hours**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  Peak hours | Day 1Correlation Coefficient *(r)* | Day 2Correlation Coefficient *(r)* | Day 3Correlation Coefficient *(r)* | MeanCorrelationCoefficient |
| Morning | 0.74 | 0.75 | 0.73 | 0.74 |
| Evening | 0.57 | 0.62 | 0.56 | 0.58 |

The mean of the correlation coefficient value is given by

 where N = 6, and x = correlation coefficient of each peak hour.

And therefore, the overall mean of the correlation coefficient obtained is approximately 0.66

Table 7 reveals that the mean correlation coefficient values during the morning and evening peak hours for day 1, day 2 and day 3 are 0.74 and 0.58 respectively, and an overall mean coefficient value of 0.66. This indicates a strong positive association for the morning peak hours and a moderate positive association for the evening peak hours.

Tables 8 and 9 presents the average delay experienced for any day at each continuous oversaturated signalized intersection for both peak hours. T5 and T7 experience the highest average persistent delay (delay due to continuous oversaturation) for any day during the morning and evening peak hours respectively. Correspondingly, T4 and T15 experience the lowest average persistent delay for any day during the morning and evening peak hours.

**Table 8: Overall average delay at each continuous oversaturated traffic**

**signal during morning peak hours**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  Traffic Light ID | Direction of Traffic Flow | Day 1 | Day 2 | Day 3 | Average delay (sec) |
| T4 | J3 – J4 | 118.07 | 284.19 | 286.53 | 229.6 |
| T5 | J6 – J7 | 1102.2 | 1263.37 | 1101.84 | 1155.8 |
| T6 | J8 – J7 | 674.5 | 887.8 | 1263.37 | 941.89 |
| T7 | J9 – J7 | 710.5 | 516.67 | 710.5 | 645.89 |
| T9 | J12 – J6 | 1076.08 | 915.31 | 1290.92 | 1094.1 |

**Table 9: Overall average delay at each continuous oversaturated traffic**

**signal during evening peak hours**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Traffic Light ID | Direction of Traffic Flow | Day 1 | Day 2 | Day 3 | Average delay (sec) |
| T3 | J5 – J4 | 652.93 | 652.29 | 651.73 | 652.32 |
| T4 | J3 – J4 | 1025.53 | 1187.31 | 1401.36 | 1204.73 |
| T5 | J6 – J7 | 1693.97 | 1855.6 | 1693.97 | 1747.85 |
| T7 | J9 – J7 | 1878.22 | 1872.64 | 1714.5 | 1821.79 |
| T15 | J9 – J10 | 545.02 | 702.9 | 705.07 | 651.00 |

**4. Discussion**

 The analyses of the total vehicular delay were carried out for the same signalized intersections at the same peak hours. T16, located at the intersection of Aka Itiam Street and Udo Umana Street (J11 – J10 direction of traffic flow), shows the lowest vehicular delay during both peak hours across all three days, and T7, located at the intersection of Oron Road and Udo Umana Street (J9 – J7 direction of traffic flow), shows the highest vehicular delay only during the evening peak hour for all three days. T5, situated at the intersection of Oron Road and Gibbs Street, faces the highest vehicle delay on both day 1 and day 2 during the morning peak hours, while T9, positioned at the intersection of Oron Road and Udosen Uko Street, experiences the highest delay in the morning peak hours on day 3 for the J12 – J6 direction of traffic flow.

 It is observed that T4, T5 and T7 situated at the intersection of Abak Road and Udo Obio Street (J3 – J4 direction of traffic flow), the junction of Oron Road and Gibbs Street intersection **(**J6 – J7 direction of traffic flow) and the crossing of Oron Road and Udo Umana Street intersection **(**J9 – J7 direction of traffic flow), consistently face continuous over-saturated traffic situations during peak hours (morning and evening) over all three days (day 1, day 2 and day 3). These fixed traffic signals are found in regions with a high population density, which are marked by a significant number of homes and places of interest. This leads to a greater volume of traffic that accounts for the persistence in continuous oversaturation. T6, situated at the intersection of Oron Road and Udo Umana Street (J8 – J7 direction of traffic flow), encounters continuous oversaturation for all three days during morning peak hours, attributed to its location on a primary thoroughfare that serves as a main access point for two nearby cities, Ikot Ekpene and Uruan. This area is marked by a significant influx of both private and public vehicles.

 T9, located at the intersection of Oron Road and Udosen Uko Street, which regulates the traffic movement from J12 to J6, experiences continuous oversaturation during the morning peak hours across all three days due to the significant inflow of traffic. T9 is positioned along a significant pathway, serving as a primary access point for entering the metropolis. It also acts as the main access road to other adjacent routes that lead to key attractions in the capital, including educational and employment hubs.

 T15, sited at the intersection of Udo Umana Street and Aka Itiam Street (traffic flowing from J9 to J10), experiences continuous congestion during evening peak hours for all three days. This location serves as the primary access point to Uyo city's main market, which is predominantly visited during the evening peak hours following the end of the workday.

 T1, located at the intersection of Abak Road and Ukana Offot Street (J1 – J5 direction of flow), experiences continuous oversaturation on days 2 and 3, whereas T3, positioned at the intersection of Abak Road and Udo Eduok Street (J5 – J4 direction of flow), faces continuous oversaturation throughout all three days during peak evening hours. Additionally, the traffic signals are situated on Abak road, which is an important route for entering and exiting major employment hubs and the nearby city of Abak. This road experiences a heavy volume of traffic flow as commuters travel into Uyo metropolis, particularly, those returning from their jobs at the Akwa Ibom state secretariat (which houses various state ministries), as well as from several vehicle repair shops.

 Table 6 shows a high positive correlation coefficient between the traffic flow ratio and green time/cycle time ratio during both peak hours for day 1, day 2, and day 3. The average correlation coefficient of 0.66 is computed from both peak hours for all three days, which indicates that an increase in the flow ratio, *Y,* demands a direct increase in the green time/cycle time ratio, λ. An effective way to positively impact on the efficiency of traffic lights that experience continuous oversaturation is to vary the values of flow ratio and green time/cycle time ratio in such a way that flow ratio should be lower than its corresponding green time/cycle time ratio at any given instant.

 Very few works have analysed the traffic situation in Uyo metropolis. The most related to this research is highlighted in [20], which examined traffic flow dynamics at signalized intersections within Uyo metropolis. [20] implemented the Canadian delay model to analyse traffic flow data that were collected from three signalized intersections (intersections of Oron Road and Gibbs Street, junction of Abak Road and Udobio Street and crossing of Ikot Ekpene Road and Ikpa Road) for three consecutive days during peak periods (morning and evening). [2] adopted the ‘Approximate Expression’ developed by [19] to analyse traffic flows from a network of eight selected traffic congestion prone intersections in Uyo metropolis and simulated same using the Matlab/Simulink software. The comparison of the simulated results and the measured data for the average vehicle delay, total queue length and saturation rate were similar. They used data collected from congestion prone unsignalized intersections for only the morning peak hours, 7.00 am to 11.00am.

 The following limitation were observed in these works; firstly, the work of [20] only considered three signalized intersections, whereas [2] focused on eight traffic intersections faced with over-saturated traffic situations. Secondly, in oversaturated flow conditions, the delay parameter, k, in the Canadian model (expressed as a function of the degree of saturation and the analysis time period) is constant, but it fails to consider the impact of fluctuating traffic demands and varying analysis time periods. The implementation of Miller’s delay model by [20] is limited to only predicting acceptable traffic characteristics at flows below the capacity of the system throughout the period of analysis. As traffic demand approaches saturation (vehicle to capacity ratio of 1.0), this model predict delays that tend to infinity. Additionally, traffic flows during peak hours are seldom stationary to achieve steady-state equilibrium which violates the models’ assumptions.

 Consequently, the Canadian delay model failed in predicting a more accurate and realistic traffic delays for T5 and T4 located at the intersection of Oron Road and Gibbs Street and the intersection of Abak Road and Udo Obio Street, where continuous over-saturated traffic conditions are experienced for both peak hours. Likewise, the application of Miller’s delay model predicted unrealistic results for the overflow queue at T4, T5, T6, T7, and T9, which are traffic signals that experience continuous oversaturation during the morning peak hours, as well as T3, T4, T5, T7, and T15 which experience continuous oversaturation during the evening peak hours. In addition to the unrealistic delay values obtained by [20], the mean overall delay of 63 seconds obtained for a vehicle at any signalized intersection was considered for only three signalized intersections, and this was computed from delay values evaluated from both peak periods.

 This research considered all signalized intersections located network-wide in Uyo metropolis. The Akçelik time-dependent model using the coordinate transformation technique was employed for the analysis of sixteen signalized intersections in Uyo metropolis. This model predicts the behaviour of real traffic, which is useful for practical purposes [15]. A major contribution of this work is predicting more precise and realistic traffic delay encountered at each continuous oversaturated signalized intersection and its corresponding traffic operating characteristics in Uyo metropolis. According to [15], the model is more effective and reliable due to the following reasons; it overcomes the limitations of other delay models in predicting traffic operating characteristics at near-capacity traffic conditions at signalized intersections by transforming the steady-state function to a transition function to produce realistic finite values.

 For flows above capacity, the overflow component of the model is the sum of a random component and a deterministic component, and for flows below capacity, the overflow component is only the random component. This is an important element in proactive traffic management as negative consequences of impending traffic congestion can be avoided through an efficient allocation of traffic flow to appropriate capacity at signalized intersections.

 It is the first time, to the knowledge of the authors, that the Akçelik delay model has been utilized to predict delay at signalized intersections in Uyo metropolis in which all signalized intersections are considered.

**5. Conclusion**

The main contribution of the study is the determination of realistic vehicular delay at each fixed-timed traffic light in Uyo metropolis based on the traffic flow data obtained. The traffic operating characteristics at sixteen signalized intersections were analysed using Akçelik time dependent model, which employed the transition function for average overflow queue to determine the vehicular delay.

 The analysis was carried out for each traffic peak hours (morning and evening) for three days and the comparison of the results obtained show that T4, T5, T6, T7, and T9 experience continuous over-saturated traffic conditions during the morning peak hours for all three days, while T3, T4, T5, T7, T15 located at the intersection of Abak Road and Udo Eduok Street, the junction of Abak Road.and Udo Obio Street, the intersection of Oron Road and Gibbs Street, the crossing of Oron road and Udo Umana Street and the junction of Udo Umana Street and Aka Itiam Street experience continuous over-saturated traffic conditions during the evening peak hours for all three days. The analysis shows that the average vehicle delay in the traffic network during the morning peak hours for T4, T5, T6, T7 and T9 are 229.6 seconds, 1155.80 seconds, 941.89 seconds, 645.89 seconds, and 1094.1 seconds respectively. Likewise, the average vehicle delay for the evening peak hours for T3, T4, T5, T7 and T15 are 652.32 seconds, 1204.73 seconds, 1747.85 seconds, 1821.79 seconds and 651 seconds respectively. The overall average delay for peak morning and evening hours are 814 and 1216 seconds.

 The estimated average values for both peak hours represent abnormal occurrences which affects vehicle travel times. Traffic lights, T4, T5, and T7 represent traffic flow direction from Uyo plaza Road to Abak Road, traffic flow direction from Oron Road/Nwaniba Road T-connection junction to Uyo plaza Road and traffic flow direction from Udo Umana Street to Uyo plaza Road respectively for both peak hours. T6 and T9 represent traffic flow direction from Uyo plaza Road to Oron Road/Nwaniba Road T-connection junction and traffic flow direction from Oron Road to Uyo plaza Road respectively for the morning peak hours. T3 and T15 represent traffic flow direction from Abak Road to Uyo plaza and traffic flow direction from Udo Umana Street to Abak Road/Aka Itiam Street respectively for the evening peak hours. It is observed that major roads affected by high traffic flows during peak hours which are associated with these continuous oversaturated signalized intersections are Oron Road and Abak Road. Oron road faces huge traffic flows from Ikot Ekpene Road, Nwaniba Road and Oron Road (which directly links Oron metropolis), whereas Abak Road faces heavy traffic flows from Atiku Abubakar way and Abak Road (which directly links Abak metropolis). These observations are consequential to the obtained average delay values, 814 and 1216 seconds. A way of tackling this problem conventionally is by the creation of a road way that directly connects Oron Road and Ikot Ekpene Road to Abak Road. The application of ITS is another way that should be considered to provide a more effective and efficient transportation management system.

 Traffic signal control is an integral component of an intelligent transportation system (ITS) that plays an important role in lessening traffic congestion. This work utilizes the Akçelik coordinate transformation technique which obtains a time-dependent model that is more applicable to signalized intersection performance and traffic conditions. This was used to obtain realistic estimates for traffic delay at fixed traffic light intersections. Traffic signal control is an effective and efficient way of tackling traffic congestion. High levels of vehicle delay can contribute to driver frustration, increasing the risk of accidents at intersections. By analysing vehicle delay data, traffic engineers can optimize signal timings, adjust lane configurations, and implement various traffic management strategies to minimize congestion and enhance overall traffic flow. Moreover, analysing vehicle delay patterns at intersections is essential for urban planning because it highlights areas where infrastructure enhancements are necessary to improve traffic flow.

 This research work will assist the Ministry of Housing and Urban Affairs responsible for urban planning and development in Uyo metropolis to implement an improved designed road traffic network that will optimize the traffic flow. It will aid in enabling the government policy makers to formulate the right policies and strategies with regards to road traffic control and management, and also enable traffic engineers to assess the operational performance of the signalized intersection to identify bottlenecks and areas of improvement. The impact of this alleviates traffic congestion and allows for a smoother transportation of goods and services around Uyo metropolis. This work is limited to Uyo metropolis and the data captures only traffic flow information for three consecutive days at traffic lights in Uyo.

 The use of Akçelik transformation technique was used in this work to obtain the average delay. It can be improved in future work by integrating heuristic algorithms such as genetic algorithm (GA) to optimize traffic signals faced with oversaturated traffic situations to minimize average vehicular delay. The application of heuristic strategies on T3, T4, T5, T6, T7, T9, T15 traffic control systems to provide intelligent green interval responses based on the dynamic traffic load inputs would reduce travel delay at these signalized intersections. Furthermore, the use of predictive analytic tools is recommended in future work for predicting the upcoming performances of these signal controls. This can be incorporated with the proposed heuristic strategies in order to enhance the efficiency of traffic system.

**Ethics statement**

This study utilized drones for data collection while adhering to the regulations governing the use of Remote Piloted Aircraft Systems/Unmanned Aerial Vehicles (RPAS/UAV) in Nigeria, ensuring the safety of both other airspace users and individuals on the ground.

**Disclaimer (Artificial intelligence)**

The authors hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript

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