PERFORMANCE ASSESSMENT OF SIGNALISED INTERSECTION USING UAV VIDEOGRAPHY: A CASE STUDY OF THE JORISSEN-BERTHA STREET INTERSECTION IN JOHANNESBURG

I AIVINHENYO*, I MOKGALAKA and T MONARENG

School of Civil and Environmental Engineering, University of the Witwatersrand,
Johannesburg, South Africa; Tel: +27 710 389686;
*Email: imuentinyan.aivinhenyo@wits.ac.za

ABSTRACT

Intersections are critical sections of a road network as they are designed to accommodate various conflicting movements. For signalised intersections with pre-timed controls in urban areas, it is essential to assess the performance of the signal timing plans at regular intervals. The objective of this study is to develop a method that could be employed to assess the performance of any signalised intersection using a typical intersection in Johannesburg as the case study. The method relies on video data gathering using Unmanned Aerial Vehicle, from which various traffic parameters such as the approach flow rate, saturation flow rate, headways and delays are measured. The performance of the intersection is assessed by comparing observed delays with theoretical delays computed using HCM delay models. The study showed that UAV video data can be processed relatively easily to measure various traffic flow parameters required to assess the performance of signalised intersections.

1. INTRODUCTION

Intersections form a critical part of highway infrastructure and their efficiency and safety are a function of its design (Fitzpatrick, Wooldridge and Blaschke, 2005). Road intersections in urban environments need to function adequately for optimal control of conflicting movements for all road users, whether motorised or non-motorised. For signalised intersections with pre-timed controls which are not responsive to demand in real-time, there is a need to carry out a performance assessment of the intersection at regular intervals to ensure that the timing plans are operating optimally. This is especially vital in environments where there is a significantly high growth rate of traffic. Inefficient timing plans could lead to congestion, increased delays and pollution, and safety problems (Adeke, Atoo & Zava, 2008). Performance assessment of signalised intersections usually requires a detailed survey of the traffic situation at the intersection. Data on flow parameters such as volume, speed, headways, saturation, delays, queue lengths, etc., are usually measured or derived for such performance assessment tasks, which can be costly and require a huge amount of resources. Pre-timed controls will usually not result in optimal traffic control compared to actuated controls since they are not responsive to fluctuations in traffic volumes across hours of the day or days of the week. They are nevertheless the easiest and cheapest type of signalised control to implement as they do not rely on expensive traffic detection or sensing devices. Due to their relatively low cost of operation and maintenance, these types of control are very popular in low and middle-income cities including South Africa.

Vehicular delay is one of the key parameters that have been widely utilised in the performance assessment of intersections (Transportation Research Board, 2010a; Saha, Chandra & Ghosh, 2017; Afrin & Yodo, 2020; Barhmaiah, Singh & Santhakumar, 2020). Other intersection performance measures as recognised in the Highway Capacity Manual 2010 (Transportation Research Board, 2010a) include volume-to-capacity ratio, queue storage ratio, pedestrian delay, pedestrian circulation area, pedestrian perception score, bicycle delay and bicycle perception score. Using the delay measure, the level of service of a signalized intersection is assessed based on the average delay experienced by vehicles in the intersection approaches. Delay can either be measured by observing the waiting time of a vehicle directly, or by comparing the travel times. In trying to avoid variations in measuring delay, researchers have developed different delay estimation models such as the HCM and Webster delay Models (Saha, Chandra & Ghosh, 2017). Other delay models such as the Australian model, Canadian model, TRANSYT model, etc. have also been documented in the literature (Akcelik, 1988).

An optimally operating traffic signal will reduce motorists' delay by providing common road space periodically to vehicular traffic from various approaches and minimizing the overall travel time of vehicles through intersections. Delay refers to the time loss of a traveller while crossing an intersection and it depends on different parameters like vehicle composition, the geometry of the intersection, driver behaviour, time of the day, type of vehicle, and availability of space. Delay is classified into stopped delay, queue delay, and acceleration-deceleration delay (Saha, Chandra & Ghosh, 2017). The total delay is a combination of all the classes of delay. Efficiency and quality of traffic operation at signal-controlled intersections are assessed in terms of total delay caused to an individual vehicle or vehicle group. As stated before, the total delay will be an indicator of the inconvenience caused to the road users and a performance measure for the intersection.

The objective of this paper is to implement an approach to assess the performance of a typical four-way signalised intersection with pre-timed signal plans, using UAV-captured video data. The performance of the intersection is assessed using a delay measure, by comparing the observed delay against the theoretically derived delay according to the Webster delay model.

2. METHODOLOGY

2.1 Study Area Description

The City of Johannesburg's central business district (CBD) has a reputation as one of the busiest districts in the whole country with high levels of traffic congestion which makes it extremely stressful to drive around the streets of the city. Several factors contribute to the traffic congestion in the city. These include accidents, malfunctioning signalized traffic control especially when there is load-shedding (no electricity power) and inefficient signalized traffic control. The relatively high number of people travelling towards the city also results creates traffic congestion. As a result, long travel times to and from places of interest within the city are a common occurrence, especially during peak periods.

In assessing and evaluating the timing plans in the city of Johannesburg, a sample intersection of Jorissen-Bertha Street is used. The coordinates of the intersection are 26º11’34” S 28º02’00”. Figure 1 shows the layout of the intersection.

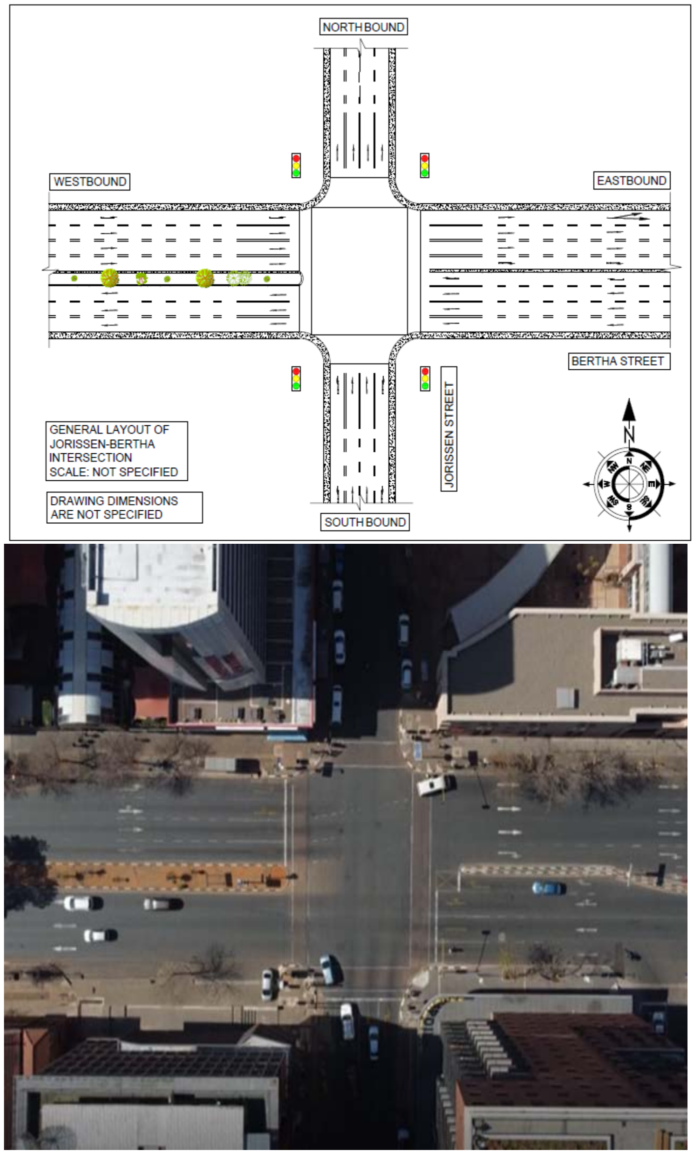

Figure 1: Layout and Drone aerial view of the intersection under study

The intersection hosts traffic in four directions. The overall widths of the intersection in the South-North and East-West directions are approximately 24m and 14m respectively. The three-phase operation of the intersection is shown in Figure 2. Represented in the figure is the permitted and protected movements for vehicular traffic. Also shown is the protected pedestrian movements. The allowed movements in each phase are shown in green while the prohibited movements are represented in red.

The South-North direction is one-way traffic while the East-West direction is two-way. Phase 1 has three movements which are the Eastbound through and left-turn movements as well as the Westbound through movement. Phase 2 includes Northbound through, left-turn and right-turn movements. Phase 3 movement includes Westbound through and right-turn movements. There is also a dedicated pedestrian signal at the intersection. At peak periods, the intersection experiences a high volume of minibus traffic to and from the inner city. The intersection also accommodates traffic from Auckland Park and Parktown areas of the city. Throughout the day, the intersection serves different categories of vehicles including regular buses and minibuses.

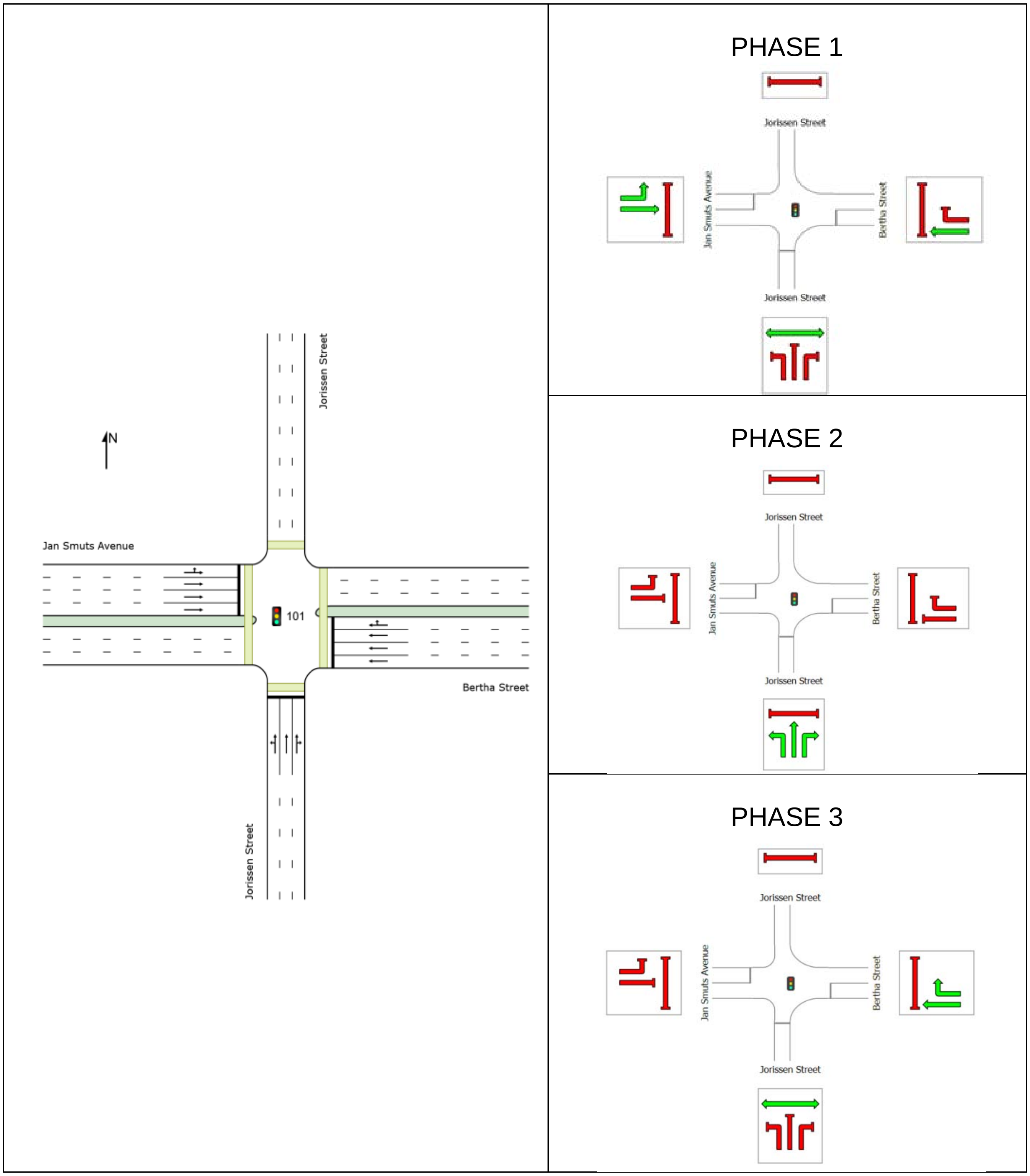

Figure 2: Three-phase movements of the Jorissen-Bertha Street intersection

2.2 Data Collection and Performance Assessment

The various steps implemented in assessing the performance of the intersection are described in the flow chart below.

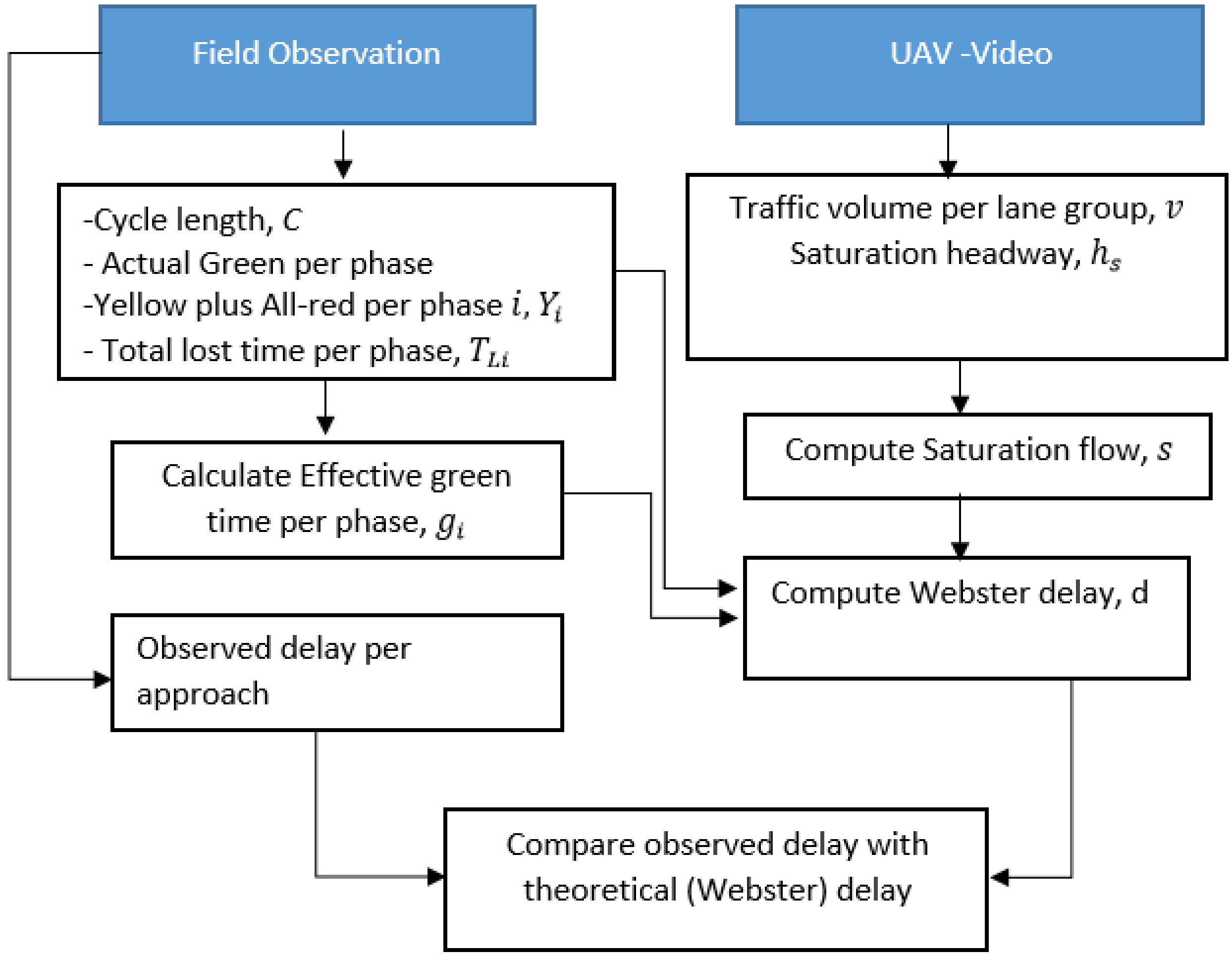

Figure 3: Approach for intersection assessment

The above approach involves two data-gathering processes that comprise manual field observation and drone video capture of the intersection. The variables observed manually include the existing timing plans of the intersection (existing timing plan data were not readily available). The timing plans were recorded by observers with the aid of a stopwatch. Each phase of the signal operations was observed and the cycle length, green time, yellow plus all-red time and total lost times per phase were all observed manually. The lost times include the start-up lost time of vehicles from the stop position and the clearance time (required to clear the intersection upon signal change from green to amber). Each variable was observed at least three times and the average value was computed. From the green time, yellow plus all-red and total lost time, the effective green time for each phase is computed using the equation:

$$g_i = G_i + Y_i + t_{Li} \quad (1)$$

Where g_i is effective green time per phase i, G_i is the actual green time per phase, Y_i is the yellow plus all-red time, t_{Li} is the total lost time per phase.

The UAV video capturing utilised the DJI Mavic 3 drone controlled by a qualified drone pilot. From the video capture, the approach volume for each leg of the intersection and saturation headway h_s between vehicles were measured from video processing. Saturation flow rates for each approach were then computed based on the measured saturation headway h_s using the relationship

$$s = \frac{3600}{h_s} \tag{2}$$

Where s is the saturation flow rate in vehicles per hour, h_s is the saturation headway in seconds per vehicle.

From the observed cycle length, approach volume and saturation flow rates, the average overall control delay per vehicle is computed using Webster's delay equation given below.

$$d = \frac{C(1-\lambda)^2}{2(1-\lambda x)} + \frac{x^2}{2v(1-x)} - \frac{0.65C^{\frac{1}{3}}}{v^2} x^{2+5\lambda} \tag{3}$$

Where d is the average overall control delay in seconds per vehicle for an approach; C is the cycle length; v is the flow rate per approach for each phase; λ is the proportion of the cycle length that is effective green for the approach or movement (that is, g/C); x is the degree of saturation, that is, the ratio of volume to capacity (v/c).

The first term in the equation represents the average delay of the vehicles, assuming uniform arrivals. The second term gives the additional delay that accounts for random arrivals and signal cycle failures. The third term is an adjustment factor that accounts for specific field conditions and is developed semi-empirically (Saha, Chandra and Ghosh, 2017).

3. RESULTS AND DISCUSSION

3.1 Observed Cycle Length and Green Time

Cycle length was observed manually using a stopwatch. Figure 4 below shows the observed cycle lengths for peak and off-peak periods for the intersection. The values shown are the averages of several observations for each phase. The cycle lengths for the peak period is observed to be longer than that for the off-peak period.

Similarly, the green interval was recorded from observations of the three phases, with values shown in Figure 5. The values recorded are the averages from a few repeated observations. The green times were further employed in computing effective green times across the three phases.

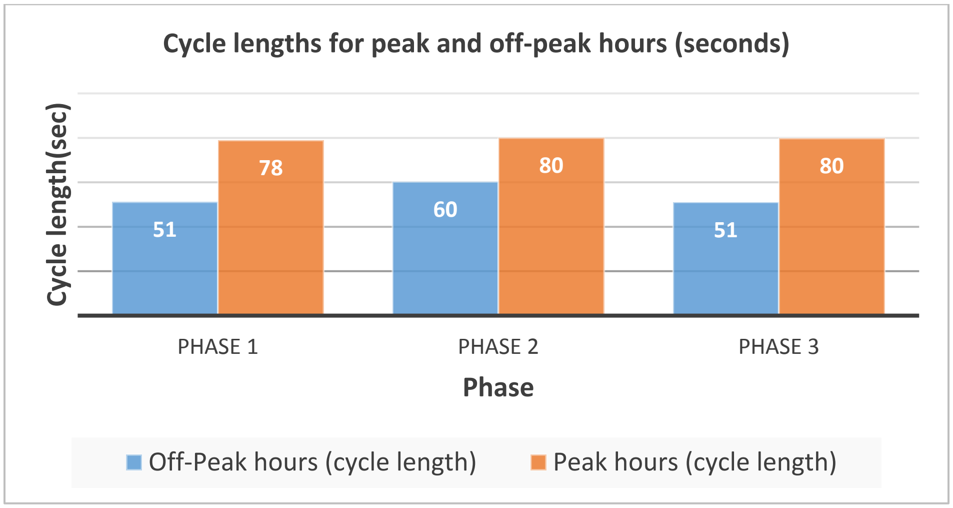

Figure 4: Cycle length for each phase of the intersection

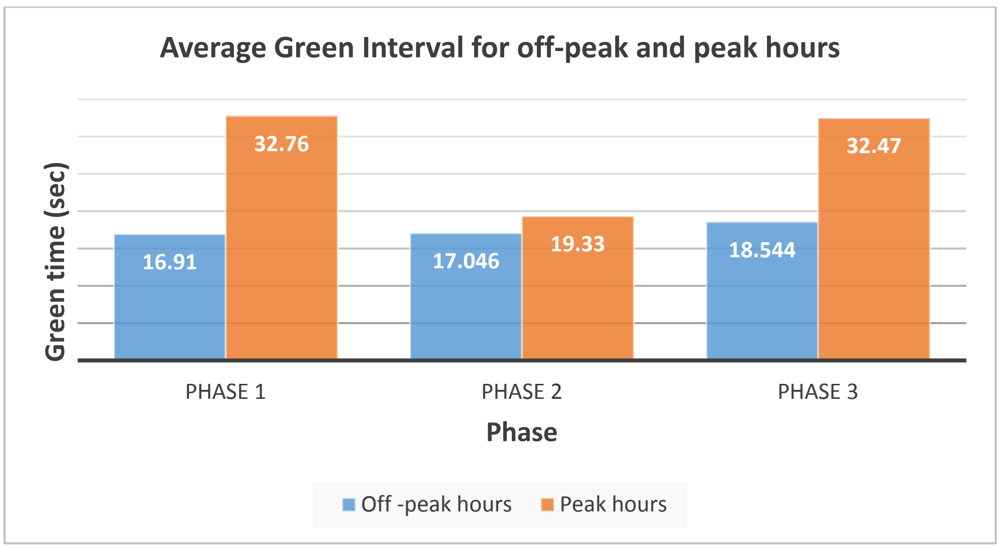

Figure 5: Observed green intervals for peak and off-peak

As seen in Figure 5, the green times for peak periods are higher than that for off-peak across all phases. Phase 2 movements experienced the least change in green time between off-peak and peak hours when compared to the other two phases.

<u>3.2 Flow Rate and Saturation Headway of Critical Movements</u>

Approach flow rate and saturation headway are the two critical variables measured from the drone video data of the intersection. One advantage of measuring these variables from the video is that it enables synchronous measurement of the variables across all approaching legs of the intersection. Such synchronous measurement using manual volume counts would require more manpower. The approach volumes in each leg were measured using a screen line created some distance away from the intersection. It was necessary to ensure that the video is captured from a stationary drone position. The saturation headway was measured using the stop line at each leg of the intersection. Table 1 below, shows the measured volume and saturation headway of the various movements across all phases of the intersection during peak and off-peak periods.

Table 1: Approach volume for all movements

Phase	Movement	Approach Volume (veh/sec)	
		Peak	Off-peak
Phase 1	EB-Through	0.324	0.317
	EB- Left turn	0.075	0.129
Phase 2	NB-Through	0.229	0.274
	NB-Left turn	0.067	0.085
	NB-Right turn	0.205	0.124
Phase 3	WB-Through	0.322	0.294
	WB-Right turn	0.110	0.161

From Table 1, it is seen that the through movements experienced the highest traffic volume for both peak and off-peak hours. The measured saturation headway and the computed saturation flow rate (using equation 2) for the critical movements in peak and off-peak periods are further presented in Table 2 below.

Table 2: Saturation headway and flow rate for critical movements

Phase	Critical movement	Critical volume (veh/sec)		Saturation headway (sec/veh)		Saturation flow rate (veh/h)	
		Peak	Off-peak	Peak	Off-peak	Peak	Off-peak
Phase 1	EB Through	0.324	0.317	3.0	2.5	1200	1440
Phase 2	NB Through	0.229	0.274	2.5	2.0	1440	1800
Phase 3	WB Through	0.322	0.294	4.0	3.0	900	1200

The measured saturation headway from video data and equivalent (computed) saturation flow rate presented in Table 2 are within the typical range of values found in the literature, including the South African Traffic Signal Design Manual (Sampson *et al.*, 2012).

3.3 Observed versus Theoretical (Predicted) Control Delays

The average vehicular delay is used as the measure of the level of service at the intersection. To determine the performance of the intersection, observed stopped delays were compared against theoretical delays obtained using the Webster delay model (Akcelik, 1988; Transportation Research Board, 2010). The delay model is given by equation 3. Figure 6 below, shows the observed and theoretical delays for peak and off-peak periods. Observed delay is taken as the average delay from all vehicles queueing during the red interval. In other words, the measured delay is the stopped delay for queued vehicles. The stopped delay was recorded from the video surveillance data. Due to the relatively short queue lengths observed during delay measurement, the maximum delay from any vehicle is no more than the red interval.

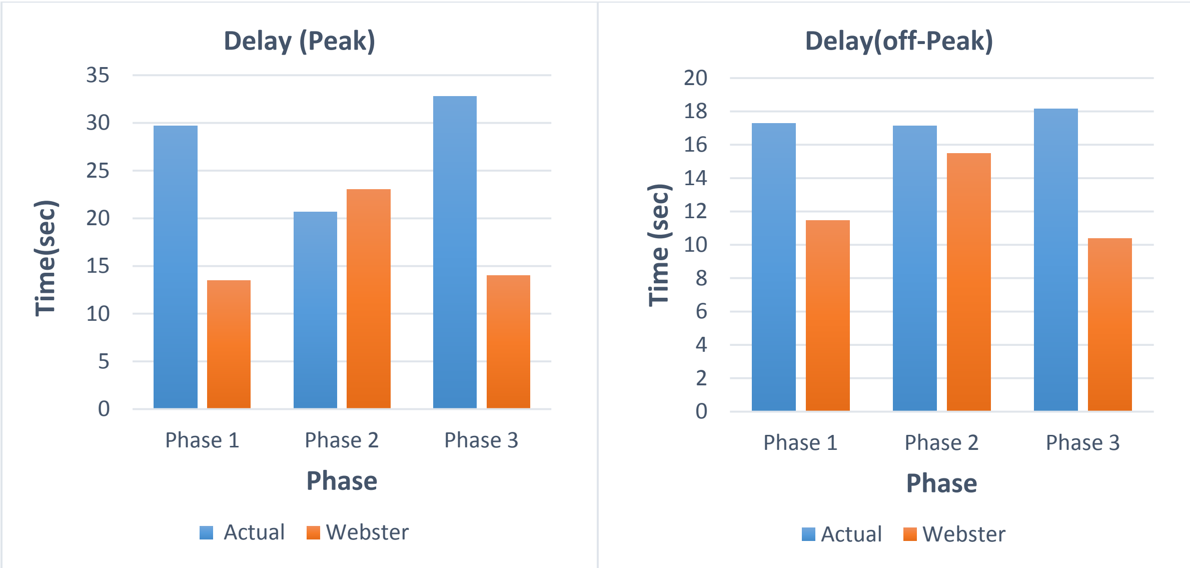

Figure 6: Observed vs theoretical delays for peak and off-peak

From Figure 6, it is seen that observed delays are relatively higher than the theoretical delays for most of the phases during peak and off-peak periods. The only exception is phase 2 of the peak period, where the theoretical delay is slightly higher than the observed delay. Since the delay is used as a reference parameter for determining the optimality of the signal timing, it can be said that the timing plan is not optimal at the time of observation. However, it is recognised that other variables such as the assumed saturation headways and the observation errors associated with manual data collection may have impacted the discrepancies between observed and theoretical delays. Further confirmation is required using more extensive data collected over a longer period. Despite the noted shortcomings, the study has revealed that signalised intersections could be assessed for performance using UAV video data supplemented by manual observations.

4. CONCLUSION

The main objective of the investigation is to demonstrate a procedure for intersection performance assessment using a combination of UAV video surveillance and manual observation of flow parameters. The intersection investigated is a typical four-way signalised intersection in Johannesburg with no existing operational or timing plan data available. Thus all variables pertaining to performance assessment were measured on the field. Among the variables measured or computed are the cycle lengths, green times, movement volumes, saturation flow rates, stopped delays and theoretical control delays. Based on observed variations in the cycle time between peak and off-peak hours, the intersection is seen to be pre-timed according to time-of-day. The observed cycle lengths are within the optimum range for both peak and off-peak hours (50-80 sec). From the results, there are slight variations in performance parameters between peak and off-peak hours. The average delay observed across the phases for peak and off-peak hours is greater than the theoretical delays according to the Webster delay model. On the one hand, this could be interpreted that the existing timing plan for the intersection is not optimal. However, more data may have to be collected over a much longer time frame (say 1 - 2 months) to fully confirm the optimality of the intersection. On the other hand, it could mean that the theoretical delay model does not adequately fit the environment, and therefore, delay models need to be calibrated based on the observed data. Such calibration is however beyond the scope of this paper which is mainly focused on demonstrating the application of UAV video for intersection performance assessment.

The study revealed that UAV video surveillance data of intersections can be processed relatively easily to measure performance parameters such as stopped delays and control delays when complemented with manual observations. There are however a few limitations with the method and some recommendations for future improvement. One such limitation is the possible errors of measurement when recording some variables such as the start-up and clearance lost times through the intersection. Getting accuracy in seconds or fractions of a second is difficult with manual observation. Having specialized equipment to measure such parameters is highly recommended. The study only considered daytime traffic conditions with no consideration for nighttime situations. The approach implemented is therefore only feasible for daytime traffic assessment. An alternative approach to data collection is recommended for nighttime traffic. In terms of the conclusion on the optimality of intersections in the city, more intersections should be investigated. There is also a need to integrate pedestrian signals in evaluating the optimality of the intersection. The scope and resources for the study however could not accommodate such integration. A public survey of motorists and pedestrians could also be implemented before data collection to understand users' views on what they would consider an optimally functioning intersection. In other words, motorists' and pedestrians' perceptions are also good indicators of performance that could complement delay measures.

5. REFERENCES

Adeke, PT, Atoo, AA & Zava, AE. 2008. 'Traffic Signal Design and Performance Assessment of 4-Leg Intersections Using Webster's Model: A Case of "SRS" and "B-Division" Intersections in Makurdi Town', *International Research Journal of Engineering and Technology*, 9001, p. 1253. Available at: www.irjet.net.

Afrin, T & Yodo, N. 2020. 'A survey of road traffic congestion measures towards a sustainable and resilient transportation system', *Sustainability (Switzerland)*, 12(11):1-23. doi:10.3390/su12114660.

Akcelik, R. 1988. 'Highway Capacity Manual Delay Formula for Signalized Intersections', *ITE Journal (Institute of Transportation Engineers)*, 58(3):23-27.

Barhmaiah, B, Singh, S & Santhakumar, S. 2020. 'Performance Analysis of Signalized Intersections on Arterial Roads under Mixed Traffic Conditions', in *7th CTSEM 2020*.

Fitzpatrick, K, Wooldridge, MD & Blaschke, JD. 2005. *Urban Intersection Design Guide: Volume 1 - Guidelines*, *FHWA/TX-05/0-4365-P2*. Available at: https://safety.fhwa.dot.gov/intersection/other_topics/fhwasa09027/resources/Urban Intersection Design Guide Volume 1 - Guidelines.pdf.

Saha, A, Chandra, S & Ghosh, I. 2017. 'Delay at Signalized Intersections under Mixed Traffic Conditions', *Journal of Transportation Engineering, Part A: Systems*, 143(8):04017041. doi:10.1061/jtepbs.0000070.

Sampson, J *et al.* 2012. *South African Road Traffic Signs Manual-Traffic Signal Design*, *Traffic Signal Design*. National Department of Transport South Africa.

Transportation Research Board. 2010a. *Highway Capacity Manual 2010 - Volume 3: Interrupted Flow*. Transportation Research Board.

Transportation Research Board. 2010b. *Highway Capacity Manual Volume 1: Concepts*. Transportation Research Board. doi:10.1017/CBO9781107415324.004.