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Extent of Delay and Level of Service at Signalised Roundabout

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ABSTRACT

The purpose of this paper is to determine the quality of highway service at signalized roundabout. Consequence, delay studies were carried out at a signalized intersection with composite traffic control mechanism. Bearing in mind that composite traffic control mechanisms are two or more traffic control devices, data for single and composite signalized intersections were analysed and compared. Results show a slightly improved level of service with roundabout, more importantly significant reduction in conflicting movement and gridlock was achieved when the traffic signals were switched off. The study concluded that signalized roundabouts have significant influence on vehicular conflict, gridlock that may reduce red light running.

Keywords: *signalized, intersections, inter-green, roundabout, delays, capacity, red light running'*

1. INTRODUCTION

Signalised intersections indicate to drivers when to enter the intersection, thus removing the problem for intuitive selection of safe gaps in the traffic flow. This in turn minimizes the probability of crashes between turning vehicles and oncoming through traffic. Signalised intersections work on the premise that motorists at the stop line are given right of way at the onset of effective green. However, when approaching a signalized intersection at high speeds and the light turns yellow it may be difficult for the driver to discern whether they should run the yellow light or brake to be safe. If the inter-green time is too short, only those vehicles that are close to the intersection will be able to continue through the intersection safely. In addition, only vehicles that are reasonably distant will have adequate time to react to the signal and stop. Those who are in between will be caught in the "dilemma zone," and won't have enough time to stop or safely cross the intersection. The only responsible thing to do, it seems, is to eliminate the dilemma zone. This would allow any vehicle, regardless of its location, to be able to safely stop or, alternatively, safely proceed during the inter-green period. This is done by making sure that any vehicle closer to the intersection than its minimum braking distance can safely proceed through the intersection without accelerating or speeding. As an alternative, signalized roundabout can be installed. As found in many studies, intersections are often accident black spots caused by a combination of reasons that range from driver lapses to red light running it can be argued. So, it's no secret that anything about an intersection that confuses or frustrates motorists heightens red-light violations. Often, simple road safety measures can significantly reduce problems at intersections. For example, the use of road signs and markings to channelize traffic through complex intersections or to provide safe waiting areas for turning vehicles can often result in substantial reductions in accidents. Other measures that have been suggested in many studies include; signal re-timing, addition of all-red clearance interval, making traffic signal lights more visible, increase in amber timings and of course installation of red light camera at strategic locations. However, accidents may occur because of a driver's inability to cope with prevailing combination of conditions as may be presented by dysfunctional traffic lights and heavy rainfall reducing visibilities, say. So, it can be argued that most of the engineering measures at signalized intersections with high traffic volume that overlook composite control measures could be deemed inadequate because of the inherent consequences of traffic light failure and their attendant gridlock. Therefore, composite traffic control mechanisms could be a useful back-up at such intersections. It reduces the complexity of an intersection and enable manoeuvres to be made in stages that would otherwise be absent in the face of traffic lights failure. It can be argued that the introduction of roundabout at high risk sites would reduce the number of decisions drivers must make at any one time thus, simplifying the driving task and assisting drivers to progress in safety and timely manner with a minimum of conflicting manoeuvres. In the light of the discussion so far, the remainder of the paper has been divided into 4 sections with the immediate section on literature review. Section 3 will focus on the setting of the studies and data collection while in Section 4 findings are discussed. Conclusions drawn from the studies are presented in Section 5.

2. SIGNALISED INTERSECTION LITERATURE

Traffic signals are one of the control mechanisms used at intersections; others include traffic signs, road markings, police, cameras, variable sign messages and roundabouts. Composite traffic control mechanisms at intersections are normally made up of two or more traffic control devices;

for example, roundabout and traffic signals combined or if you like, traffic signal and one way flow combined. Roundabouts work on the principle of circulation and entry flows; whereas signalized intersections rely on staging or phasing for effectiveness. Safety at roundabouts is enhanced by limiting circulating speeds and this is achieved by entry path curvature. The control strategy of traffic signal is flexible; it hinges on vehicle actuation or fixed time operation. However, there are some vexing traffic safety issues worth considering at signalized intersections; for example, in the event of signal breakdown or malfunction, how would such intersections cope with gridlock; what are the delay trade-offs for installing a standard roundabout at existing signalized intersections or vice versa. Roundabouts work on the principle of circulation and entry flows, where the maximum entry flow rates depend largely on circulating flow bearing in mind that entry flows must give way to circulating flows. Where an existing roundabout is signalized, changes to the geometry may be necessary to achieve an optimum design [2]. Signalised intersections rely on staging or phasing movements as well as geometric design for effectiveness. In circumstances where an intersection has traffic signal with stage movements, conflicting entry/circulating relations are minimized if not actually removed provided entry flares are converted to parallel lanes. This will not be the case at signalized intersections with phasing movements because a phase describes movements which can take place simultaneously. For example at a conventional crossroad where there are major conflicts between the north-south traffic stream and the east-west traffic stream but where there is a heavy presence of right turning movements; the circulating flow associated with the right turning movements will stifle entry movements significantly. Consequently, signalized roundabouts are more effective when operated on staging rather than phasing movements. Performance evaluation of signalized intersections can either be single or multi sites. In the case of single sites, vehicles have to contend with one stop line only, whereas at multiple sites, the signal operations are two or more stop lines tied together. Since multi-sites hold intermediate features (cruise speed, link length and number of lanes) between the nodes evaluating delays could be problematic. There are computer programs like LINSIGS and TRANSYT that use an iterative process to determine signal timings and delays. In TRANSYT saturation flows can be generic (1900 pcu/h –straight, 1800pcu/h for right turning, 1700pcu/h for left turning) or empirical inputs.

2.1 Delays and Queues at Intersection

Delays and queues are often presented as level of service (LOS). According to HCM, level of service is ‘a qualitative measure that characterizes operational conditions within a traffic stream and their perception by motorists and passenger’. HCM prescribes control delay per vehicle (s/veh) as;

$$\partial = \frac{0.5C\left(1-\frac{g}{c}\right)^2}{1-\left[min(1,X)\frac{g}{c}\right]}\left(\frac{(1-P)f_{PA}}{1-\left(\frac{g}{c}\right)}\right) + 900T\left[(X-1)+\sqrt{(X-1)^2+\frac{8kIX}{QT}}\right] + \partial_3 \qquad (1)$$

Where;

c = cycle length (s);
g = effective green;
X = v/c ratio for lane group;
P = proportion of vehicles arriving on green;
f_{PA}= supplemental adjustment factor for platoon arriving during green,
T = duration of analysis period,
k = incremental delay factor that is dependent on controller settings,
I = upstream filtering/metering adjustment factor,
Q = lane group capacity

The optimum cycle times (C_o) for an intersection could be obtained by the use of the following equation;

$$C_o = \frac{1.5L+5}{1-\Sigma y} \qquad (2)$$

Where;

L = total lost time per cycle;

$\Sigma y = \Sigma\frac{q}{Q_s}$;

q = demand flow; and Q_s = saturation flow;

Note that saturation flows were taken as 1900 pcu/h for flows going straight, 1700pcu/h for right turning movements and 1800pcu/h for left turning movements as prescribed by UK Transport Research Laboratory in the TRANSYT computer program. Saturation flows and lost times can also be estimated using model equations as well as empirical data obtained from site surveys. In any case, equation 1 can be partitioned into four parts, $\boldsymbol{\partial}_1$ (uniform control delay assuming uniform arrivals), $\boldsymbol{\partial}_2$ (incremental delay to account for random arrivals and oversaturation queues, assuming no initial queue) $\boldsymbol{\partial}_3$ (initial queue delay which is taken as zero when there is no initial queue) and PF (progression adjustment factor).

$$\boldsymbol{\partial}_1 = \frac{0.5C\left(1-\frac{g}{c}\right)^2}{1-\left[min(1,X)\frac{g}{c}\right]};\ PF = \left(\frac{(1-P)f_{PA}}{1-\left(\frac{g}{c}\right)}\right);$$

$$\boldsymbol{\partial}_2 = 900T\left[(X-1)+\sqrt{(X-1)^2+\frac{8kIX}{QT}}\right] \qquad \text{see equation 1}$$

In the United Kingdom, steady state queuing and delay approach is often used, which is a fusion of delays due to a uniform rate of vehicle arrival, random nature of vehicle arrivals and simulation of traffic flow. Hence average delay per vehicle is taken as;

$$\partial = \frac{c(1-\lambda)^2}{2(1-\lambda x)} + \frac{x^2}{2q(1-x)} - 0.65\left(\frac{c}{q^2}\right)^{1/3} x^{(2+5\lambda)} \qquad (3)$$

Where;

c = cycle time (s);
λ = proportion of the cycle that is effectively green for the phase under consideration (effective green time/cycle time),
q = flow,
s = saturation flow,
x = degree of saturation, which is the ration of actual flow to the maximum flow that can be passed though the approach (q/ λs)

Equation 3 can be partitioned into three parts:

$\boldsymbol{\partial}_1$ (delays due to a uniform rate of vehicle arrival),
$\boldsymbol{\partial}_2$ (random nature of vehicle arrivals),
$\boldsymbol{\partial}_3$ (simulation of traffic flow)

$\boldsymbol{\partial}_1 = \frac{c(1-\lambda)^2}{2(1-\lambda x)}$;
$\boldsymbol{\partial}_2 = \frac{x^2}{2q(1-x)}$;
$\boldsymbol{\partial}_3 = 0.65\left(\frac{c}{q^2}\right)^{1/3} x^{(2+5\lambda)}$ see eqn. 1

When demand reaches capacity, equation 3 above cannot be used because an infinite delay is predicted, therefore time-dependent queuing delay model equation 4 can be used as;

$$\partial = 1/2\left[(F^2+G)^{1/2} - F\right] + e + L \qquad (4)$$

Where;

$$F = \frac{1}{\mu_o - q_o}\left\{1/2T(\mu - q)\left(1-\frac{h}{q}\right) + 2R\left[1 - h\left(\frac{1}{q}+\frac{1}{\mu}\right)\right]\right\} + e$$

$$G = \frac{2T}{\mu_o - q_o}\left[2R\left(\frac{q}{\mu}\right) - (\mu - q)\, e\right]\left(1-\frac{h}{q}\right)$$

$$h = \mu - \mu_o + q_o$$

$$e = \frac{2Rq_o}{\mu_o(\mu_o - q_o)}$$

For q_o=demand for the preceding time interval;
μ_o = capacity for the preceding time interval; and
T = length of the modelled period

ArahanTeknik (Jalan) 13/87 [1] employs equation 5 when estimating delays at signalized intersections

$$\partial = \frac{9}{10}\left[\left(\frac{c(1-\lambda)^2}{2(1-\lambda x)}\right) + \frac{x^2}{2q(1-x)}\right] \qquad (5)$$

Where;

C = cycle time, λ = g/c, q = flow, and s = saturation flow and x = q/λs

2.2 Dynamic Passenger Car Equivalency

PCE values have been used extensively in the Highway capacity Manual (HCM) (1994) (1997) to establish the impact of trucks, buses and recreational vehicles on traffic operations. It was defined in HCM (1965) as 'the number of passenger cars that are displaced by a single vehicle of a particular type under a prevailing traffic and road conditions. For two-lane highways, PCEs are given as a function of the type of terrain, and level of service or average upgrade speed for trucks, buses and recreational vehicles according to Transportation Research Board Special report 209 (1994). Since the 1965 *HCM* numerous other techniques have been applied. They can be summarized as; PCEs based on headways; PCEs based on delay; PCEs based on platoon formation; PCEs based on speed; PCEs based on vehicle-hours. According to Seguin,[6] PCEs can be defined as the ratio of the mean lagging headway of a subject vehicle divided by the mean lagging headway of the basic passenger car. There is no need to derive a new model equation for the studies because such equations will have little effect on the result outcomes. Besides, the headway method is one of the several techniques for measuring PCEs. By using the headway method one is implying that the relative amount of space occupied by a vehicle in motion is the basis for calculating PCE values. The simplistic approach based on vehicle headways may be estimated as:

$$PCE_{ij} = \frac{H_{ij}}{H_{pcj}} \qquad (6)$$

Where:

PCE_{ij} is the PCE of vehicle Type I under Conditions j, and H_{ij},
H_{pcj} is the average headway for vehicle Type I and passenger car for Conditions j.

PCE values for Signalised Intersection in Malaysia are as follows; Passenger cars 1.00, Motorcycles 0.22, Medium/ light Lorries 1.19, heavy Lorries 2.27, Buses 2.08 [1]. The use of such equivalents is central to highway capacity analysis where mixed traffic streams are present. By using a simplistic ‘headway of vehicle type’ approach we can at least point the passenger car equivalent values for intersection in a particular direction.

In the study, the headway approach was used to test the validity of Malaysia’s signalised intersection PCE values. It passed marginally. The vehicle types distinguished in this study were as follows: Class 1: Passenger cars, small vans and utilities; Class 2: Lorries with 2 axles and mini buses; Class 3: Trailers with more than 2 axles; Class 4: Buses; Class 5: Motorcycles [1]. The capacity for a signalized intersection depends on the green time for the approaches. If the saturation flow for the approach is s veh/hr, then the capacity (Q) for the approach is as in Equation 8.

$$Q = S\left(\frac{g}{c}\right)\text{veh/hr} \qquad (7)$$

Where: Q = capacity, q = effective green time, c = average cycle time, S = saturation flow

Determination of capacity at a roundabout is given by predictive equation for entry capacity where;

$$Q_E = k(F - F_c Q_c) \quad \text{When } F_cQ_c \leq F \qquad (8)$$

For, Qc = circulating flow;
k = 1 – 0.00347(Ø – 30) – 0.978((1/r)-0.05);
F = 303X_2;
fc = 0.210t_D (1 + 0.2x_2);
t_D = 1 + 0.5 / (1 + M);
M = exp [(D – 60) / 10];
X_2 = v + (e-v) / (1 + 2S);
S = .6(e – v) / l;

3. DATA COLLECTION

Based on the hypothesis that gridlock at four-arm intersection irrespective of what triggered it is unacceptable to motorists, and will lead to significant delay the setting of with and without signalised roundabout is shown below in figure 1.Studies were carried out at Skudai highway-5 south signalised intersection during peak period. Skudai highway-5 south is a principal road in Skudai town, Malaysia. Malaysia has extensive roadways that connect all major cities and towns on the western coast of Peninsular Malaysia. Most road accidents in Malaysia happen on federal roads, state roads and municipal roads according to police statistics. Most of the accidents are caused by the attitude of certain road users who drive dangerously over the speed limit. Some are clearly avoidable. Accident statistics in 2009 showed that about 22% of accidents were at intersections. This percentage is expected to rise in 2011.

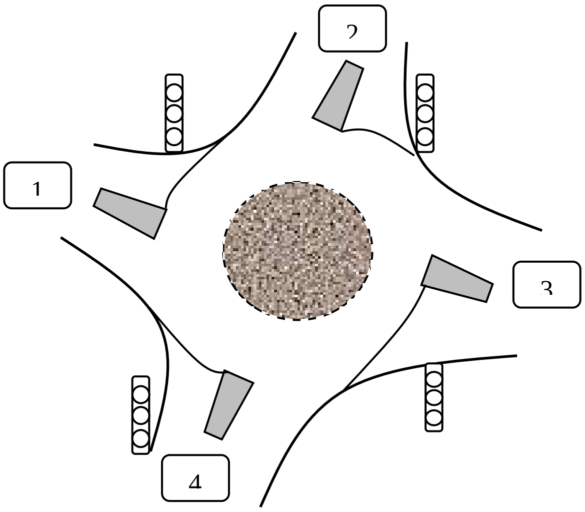

Figure 1. Setup of Signalised Roundabout Study

4. FINDINGS AND DISCUSSION

The primary interest of the study is comparative delay assessment, so, the choice of predictive model equation need not affect the outcome significantly. Moreover, results from manual computations would be compared with those from ARCADY computer program for consistency. It can be mentioned in passing that ARCADY was developed by UK Transport Research Laboratory (TRL) to model queues and delays at roundabouts. Output for the program includes tables of demand flows, capacities, queue lengths and delays for each time segment, together with a diagrammatic representation of the growth and decay of the queues on each arm. Since roundabout delay and capacity estimation method would rely on ARCADY outputs, TRANSYT was used to compute delay and queue as well as the optimum co-ordinated signal timing. The studies employed a stepwise problem solving approach described below. The step wise approach described below is not rigid. It can be adjusted as deemed fit considering that circumstances vary from place to place.

Step 1: Determine the road hierarchy, geometric alignments and the state of pavement surface as well as drainage system in other to eliminate or minimize delay effects associated with them

Step 2: Determine whether the intersection employs static (pre-timed) or actuated signalization system.

Step 3: Determine whether the signalised intersection employs staging or phasing

Step 4: Determine number of arms, turning movements and demand flows

Step 5: Determine saturation flows and lost time
Step 6: Determine cycle time as well as signal timings
Step 7: Determine delays and level of service

Step 8: Design standard roundabout at the intersection repeat steps 2 to 6

Step 9: Disengage traffic signal so as to allow the intersection to operate as an unsignalised roundabout.

Step 10: Determine reserve capacity of roundabout, delay and level of service

Step 11: For consistency, use turning movements and demand flow in step 4for step 10

Step 12: Compare level of service outcomes

In tables 2 below take note that, $\boldsymbol{\partial}$ = delay, lost time per cycle = 12s; left turning movements are omitted because they do not interfere with other movements and not directly affected by traffic signal timings from the beginning of the left flare lane until exit and also that;

$$\sum y_{max} = 0.31+0.16+0.26+0.08 = 0.81,\ Co = 121s.$$

Table 2A Existing Peak Flows (pcu/h) at Signalized Intersection

Stage	Demand Flow	Approach	Demand Flow	Saturation Flow
1	1214	Ahead	593	1900
		Ahead/Right	226	3600
2	611	Ahead	180	1900
		Ahead/Right	337	3600
3	1144	Ahead	496	1900
		Ahead/Right	202	3600
4	384	Ahead	90	1900
		Ahead/Right	285	3600

Table 2B Existing Peak Flows (pcu/h) at Signalized Intersection

Stage	$\frac{q}{Q_s}$	Actual green	$\frac{v}{Q}$	$\boldsymbol{\partial}$ (s)	LOS
1	*0.31*	45s	0.84	56	E
	0.06				
2	*0.16*	23s	0.49	38	D
	0.09				
3	*0.26*	38s	0.83	58	E
	0.06				
4	*0.05*	11s	0.87	68	F
	0.08				

In tables 3 below, take note that: $\boldsymbol{\partial}$ = delay, lost time per cycle = 12s; left turning movements are omitted because they do not interfere with other movements and not directly affected by traffic signal timings from the beginning of the left flare lane till exit and also that;

$$\sum y_{max} = 0.39+0.15+0.23+0.05 = 0.82,\ Co \cong 121s.$$

Table 3A Predicted Peak Flows (pcu/h) at Signalized Roundabout

Stage	Demand Flow	Approach	Demand Flow	Saturation Flow
1	1214	Ahead	748	1900
		Ahead/Right	188	3600
2	611	Ahead	103	1900
		Ahead/Right	537	3600
3	1144	Ahead	156	1900
		Ahead/Right	838	3600
4	384	Ahead	91	1900
		Ahead/Right	178	3600

Table 3B Predicted Peak Flows (pcu/h) at Signalized Roundabout

Stage	$\frac{q}{Q_s}$	Actual green	$\frac{v}{Q}$	$\boldsymbol{\partial}$ (s)	LOS
1	*0.39*	59s	0.81	48	E
	0.05				
2	*0.05*	23s	0.49	38	D
	0.15				
3	*0.08*	38s	0.74	50	E
	0.23				
4	*0.05*	11s	0.52	46	D
	0.05				

The main thrust of this study is to determine the merits or otherwise, of signalised roundabout. Analysis of the existing traffic performance at the signalised intersection suggests that arm 4 has the worst delay even though it posted the lowest demand flow. A simple explanation could be that ahead and right turning movements constitute 74% of the total demand flow. Given that it has an assigned 14seconds effective green time, it may be argued that in the event of traffic signal failure, arm 4 would be worst affected. Arm 2 and Arm 4 are on the minor roadway; however, arm 2 posted level of service D with an effective green time of 26seconds. The simple explanation here is that arm 2 has a larger traffic flow on the ahead only lane where the saturation flow is 1900 pce per hour that translates to higher proportion of green time than arm 4. From observations at the site arms 1 and 3 traffic operation under performed largely due to motorist making U turns at the onset of green light. U-turns are allowed at the intersection. They are affecting generalized traffic movements at all arms, probably explaining why a proposed composite traffic control should be given serious consideration. Rather than make tight U turns, motorists can make orderly turns if a roundabout is installed at the intersection. Signalized intersections have conditioning effects on drivers' behaviour it can be argued; one of the consequences is decision making by motorists on approach to stop line [2]. In the event of signal breakdown or malfunction, how would motorists at such intersections cope with gridlock? What are the delay trade-offs for installing a standard roundabout at existing signalized intersections or vice versa? It can be queried. Findings from the study have shown a slightly improved level of service with a roundabout, more importantly significant reduction in conflicting movement and gridlock was achieved when the traffic signals were switched off.

5. CONCLUSIONS

The study concluded that at signalised intersections, composite traffic control mechanisms have significant influence on vehicular conflict, gridlock and red light running compared with a single controlled intersection with traffic signals. Based on the analysis of empirical data, the following conclusions can be drawn;

- Signalised roundabout is the preferred option at signalised intersections in cases where road safety is heightened and traffic flow is high;
- Signalised roundabout will not lead to reduced quality of service
- Although roundabouts would normally equalize all approach arms, which is at a disadvantage to major roads at peak period, the presence of functional traffic lights would restore priority flows
- The suggestion that roundabout installation at existing signalised intersection would lead to additional delay is void

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