# DERIVATION OF A SIGNAL TIMING SCHEME FOR AN EXTERNALLY SIGNALIZED ROUNDABOUT

by

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## Abstract

Among the traditional forms of intersection control, signalisation and roundabouts are widely used at intersections where traffic volumes are high. It can be shown that by combining signals with a roundabout higher level of service can be achieved under certain traffic and geometric conditions.

This paper discusses a procedure to check the suitability of signalising a roundabout and to determine the phasing and timing sequence if an externally controlled signalised roundabout is selected. A case study is presented to illustrate the findings and to compare the level of service of a signalised roundabout operation with signalised intersection operation and a normal roundabout operation.


## 1.0 Introduction

An intersection is defined as a location at which two or more streets intersect at grade. As the common right of way at an intersection should be shared by the traffic from each approach, capacity of individual approaches gets reduced. Due to the conflicting nature of the turning movements of vehicle and pedestrian flows at an intersection, the capacity through the intersection reduces further, causing delays and accidents. Hence, a mechanism to separate conflicting movements should be implemented to improve the capacity.

The separation of conflicting movements can be done either by separating them in time or by separating them in space. As the separation in space (grade separation) is very expensive, separation in time is widely used. This is mainly done by setting priorities to each movement by means of a control mechanism.

However, separation in time is always associated with time losses and delays to traffic flow. It is very important to select a proper control mechanism that minimises the delays and losses. As the efficiency of an intersection control mechanism depends on intersection geometry and the traffic flow, it is absolutely necessary to design the intersection control mechanism to suit the site conditions. This process can be divided into two parts as

(i). the selection of a suitable control measure and

(ii). the design of the intersection geometry and control mechanism to get the optimum output.

## 2.0 Signalised Roundabouts

A wide range of intersection control measures are available, varying from uncontrolled, sign control, manual control etc. to roundabouts and traffic signals. Among the traditional forms of intersection control, signalisation and roundabouts are widely used at intersections where traffic volumes are high. It is the general practice that when roundabout capacity is reached, signalisation is considered with the demolition of the roundabout. However, in Sri Lanka as in many other countries and especially in urban areas, the inability to acquire land required for re-design, is often a limiting factor. Moreover, the marginal increase in capacity is usually not adequate to provide the desired Level of Service anticipated from such an investment. The next higher level of intersection control which is grade - separation is usually prohibitively expensive. Thus, an investigation is made on the feasibility of signalising a roundabout.


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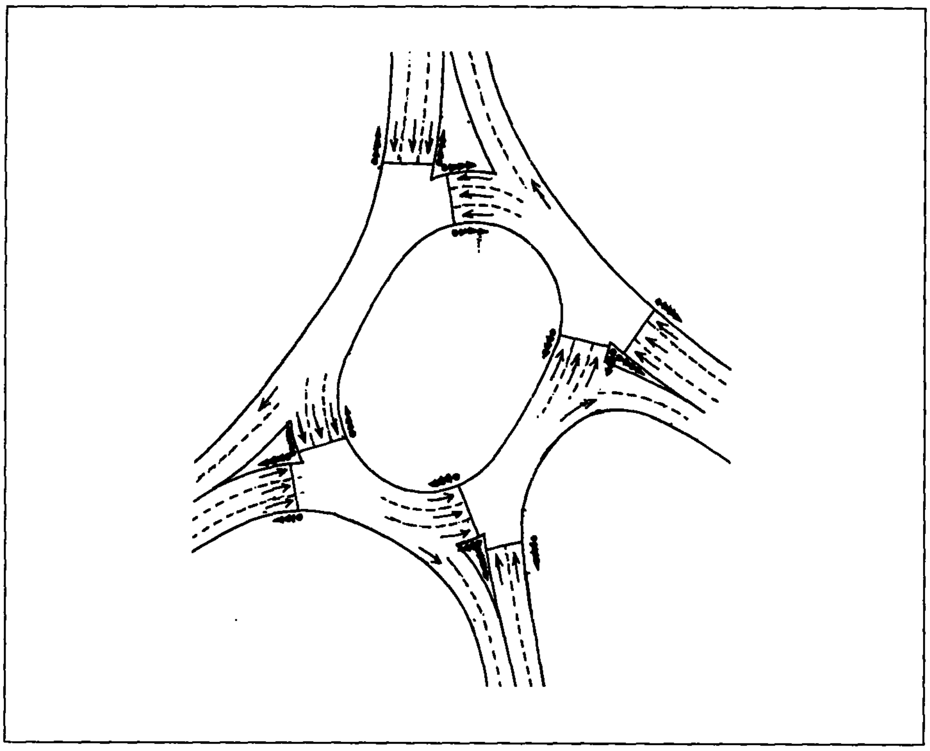

**Figure 1: Internally Controlled Signalised Roundabout**

There are two ways of signalising a roundabout. An internally controlled signalised roundabout is usually (Figure 1) suited for very large rotary intersections. In this method of control, the external entry flow as well as the internal circulatory flow is controlled by signalisation.

In the second type, referred to as externally, controlled signalised roundabout, only the external entry flow is controlled by signals with the internal circulatory flow operating under roundabout right - of - way rules (Figure 2).

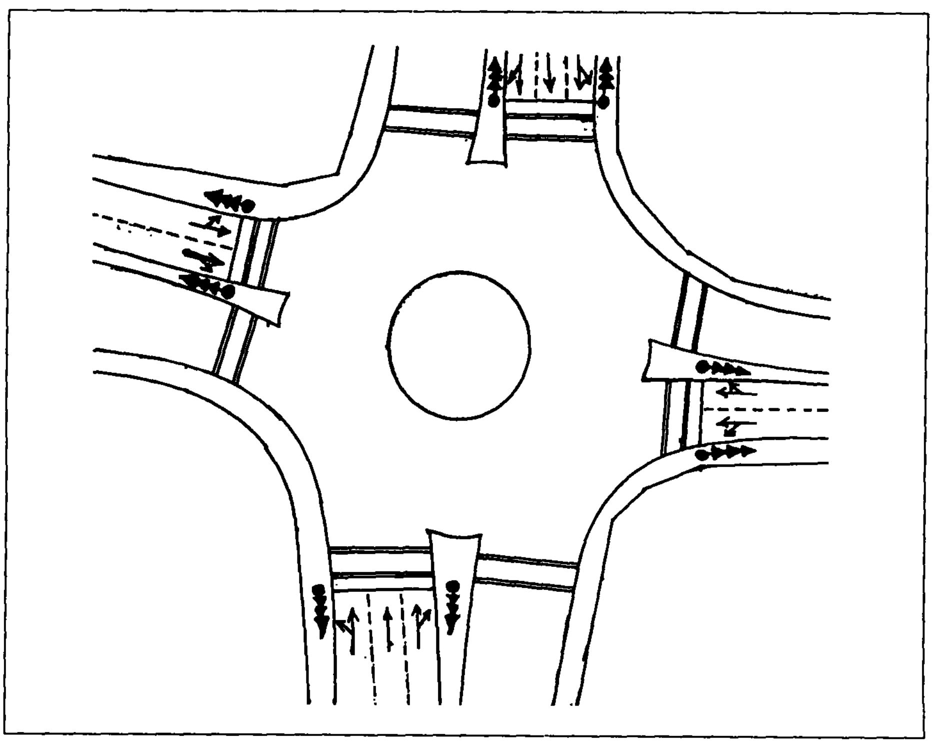

**Figure 2: Externally - Controlled Signalised Roundabout**

The Externally Controlled Signalised Roundabout (ECSR) is most suited for consideration in Sri Lanka, where a large number of smaller roundabouts are presently in operation.

The comparative advantages of the ECSR viz-a-viz conventional roundabouts and signalised intersections are given in Table 1.

from through traffic. However, at an externally controlled signalised intersection the situation is different to the above as right turning vehicles get the right of way over the through movement at the roundabout. Here, the capacity through the intersection is governed by the roundabout capacity.

**Table 1: Advantages of Externally Controlled Signalized Roundabouts**

| Over Signalisation | Over Roundabouts |
|---|---|
| 1. Can accommodate U - turns.<br>2. Circulatory area can be utilised for storage of right - turns without disturbing through traffic.<br>3. Since right - turning traffic gets right of way, better suited when directional split of traffic is high.<br>4. Delays less since a two - phase system could be used, where a signal intersection would require 3 or 4 phase. | 1. Better control of pedestrian flow.<br>2. Better utilisation of circulatory space.<br>3. Jamming of intersection is prevented due to proceeding signal control.<br>4. Less delays when flows are high and when approach flows are imbalanced.<br>5. Can be operated as a traditional roundabout during off-peak hours, with signals switched off or in flashing mode. |

This paper presents a theoretical methodology for determining the timing and phasing sequence for a ECSR. The paper also discusses the steps and checks to be followed in such an exercise in order to maintain circulation, pedestrian crossing facilities and the required level of safety.

## 3.0 Theoretical Development

### 3.1 Introduction

The main objective of installing traffic signals is to manage the sharing of the common right-of-way by separating conflicting movements in time. The effectiveness of a signal scheme will depend on the signal phasing sequence and its timing. Here, a phase is defined as a part of a signal cycle during which selected traffic movements receive the right of way simultaneously. The generally accepted approach is to select a phasing scheme with the minimum number of phases to accommodate the traffic under a given condition. When the number of phases per cycle increases, time losses and delays to traffic will increase.

When right turns are allowed to share the right of way with through traffic, capacity through a signalised intersection reduces due to the conflicting nature of movements. Therefore, when traffic flow increases it is necessary to consider a signal scheme with higher number of phases (more than 2) to separate right turns

Therefore, the possibility of using a two phase signal scheme at a signalised roundabout will be higher than that for a signalised intersection when the proportion of right turns is higher or when the gap availability for right turns is less. However, there should be adequate storage for both left and right turns between the intersection and the pedestrian crossings on the respective departure roads. This space should be sufficient for storage of turning vehicles without queuing back to obstruct the circulatory area.

### 3.2 Phasing Scheme & Cycle Time

Consider an externally controlled signalised roundabout as shown in the Figure 3 below. When there are n-number of phases, the cycle time, C, for the signal scheme is given by

$$C = \sum_{j-1}^{n} G_j + \sum_{j-1}^{n} A_j + \sum_{j-1}^{n} r_j^{all} + \sum_{j-1}^{n} rla_j$$

Where,

| | | | |
|---|---|---|---|
| Where, | $G_j$ | = | Green time for Phase j |
| | $A_j$ | = | Amber Time for Phase j |
| | $r_j^{all}$ | = | all red time for Phase j |
| | $r/a^j$ | = | red amber for Phase j |

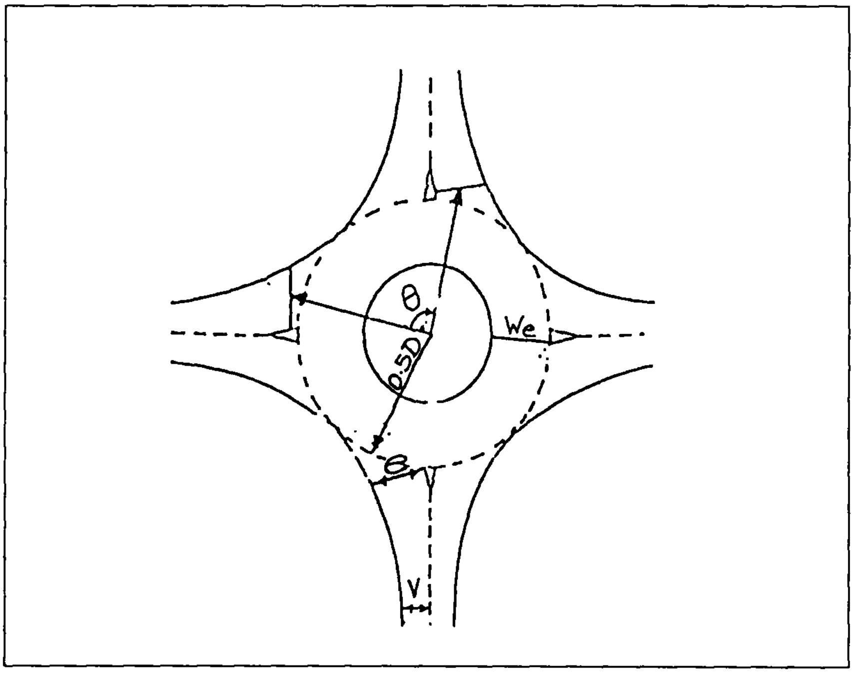


**Figure 3**

The actual green times, Gj, are calculated based on the effective green times gj, for each phase. Effective green times will be determined based on the traffic flow after subtracting any time losses per cycle. Time allocated for all red, red amber and a small fraction of green (starting delay) is considered as loss time in timing calculations. It is reasonable to assume a 1 sec. starting delay and 0.75-1 sec. red amber period per cycle. All red time should be calculated based on the time required to clear the intersection for a vehicle which enter the intersection at the end of amber period.

If $\theta(i,i+2)$ - angle between center of the stop line in approach i to approach i+2

$D$ - inscribed circle diameter

$W_c$ - circulating width

$U_v$ - average circulating speed of vehicles

$$r_i^{all} = \mathrm{Max}^{m} \left\{ \frac{\theta\,(i, i=2)\,(D - W_c)}{2U_v} \right\}$$

i = approaches allowed in phase j

j = 1 to n where n- number of phases

## 3.3 Minimum Cycle Time For Pedestrian Requirement ($C_{ped}$)

As the presence of pedestrians reduces the intersection capacity, it is necessary to separate conflicting pedestrian movements from traffic flow. The accepted practice is to allow pedestrian movements in the direction parallel to the through traffic movement allowed at that time. However, if pedestrians are allowed, it is necessary to provide sufficient time for them to cross the given approach.

Let tj be the time requirement for pedestrians during a given phase j

$$t_j = \frac{2}{U_w}\, \mathrm{max}^{m}\,(V_{i-1}, V_{i+1})$$

$2V_i$ - width of approach i

$U_w$ - walking speed

i - approaches in which through traffic movements are allowed for phase j.

Then,

$$G_j + A_j = \frac{2}{U_w}\, Max^{m}\,(V_{i-1}, V_{i+1})$$

$$C_{ped} = \sum_{j=1}^{n} \left[ \frac{2}{U_w}\, Max^{m}\,(V_{i-1}, V_{i+1}) + r_i^{all} + r/a_j \right]$$

## 3.4 Maximum Cycle Time Based on Right Turn Storage : ($C_{rts}$)

Though the right turning vehicles should get the priority at the roundabout, all right turns may not get their right of way. If all the right turns arriving during one cycle can be accommodated within the roundabout without obstructing through traffic movement, a two phase signal will be satisfactory.

Let $q_{ir}$ - Volume of right turning vehicles on approach i per hour

$n_i$ - the number of right turns from ap proach i that can be stored within the roundabout without obstructing the through traffic.

then

$$C_{rts} = Min^m \left[ \frac{3600 . n_i}{q_{ir}} \right] \quad \text{for i number of approaches}$$

The right turn storage, $n_i$ is a function of the circulating width, $W_c$ and the diameter of the roundabout, D.

### 3.5 Determination of the Phasing Scheme

If the $C_{rts}$ calculated above is greater than the $C_{ped}$ a two phase scheme can be selected, provided roundabout capacity is sufficient during the two phases selected. The roundabout capacity for a given flow condition is given by [D.O.T ( 1981)].

$Q_E = k(F - f_c Q_c)$ when $f_c Q_c$ is less than or equal to F

$= 0$ when $f_c Q_c$ is greater than F.

Where

$Q_E$ = Entry flow in pcu/hour (1 HGV = 2 pcu)

$Q_c$ = Circulating flow across the entry in pcu/hour

$k = 1-0.00347(f - 30) - 0.978\{(1/r) - 0.05\}$

$F = 303x_2$

$f_c = 0.210t_D (1+0.2x_2)$

$t_D = 1 + 0.5/(1+M)$

$M = \exp\{(D-60)/10\}$

$x_2 = V + (e-v)/ (1 + 2S)$

$S = 1.6 (e-v)/ l'$

and e,v,$l'$S,D,$\phi$, and r are geometric parameters.

If the roundabout capacity is not sufficient or $C_{ped} > C_{rts}$ a two phase scheme cannot be used, and higher order phasing scheme should be considered.

However, $C_{rts}$ calculated above would be an extreme upper bound for the cycle time. In practice, some of the right turns may get the right of way to clear the intersection. As $q_{ir}$ is a random quantity and there is no established procedure to estimate the fraction of right turns that would get the right of way to clear the intersection, it is reasonable to assume that at least 25% of the $q_{ir}$ will clear the intersection during the effective green period. Adjusted cycle time, $C'_{rts}$, calculated based on this assumption could be used as an alternative if $C_{ped} > C_{rts}$. In this situation care should be taken to assure that sufficient roundabout capacity is available.

### 3.6 Determination of Cycle Time

If a two phase scheme is satisfactory "Webster" formula [Webster & Cobbe (1966)] given below to calculate the cycle time at isolated signalised intersections can be used to calculate the cycle time subject to the above lower and upper bound constraints.

$$C = \frac{1.5L + 5}{1 - \sum_{j=1}^{n} \frac{q_j}{S}}$$

Where

L - total lost time in critical lanes during one cy cle

$q_j$ - critical lane volume in Phase j in equivalent through Passenger Car Units (PCU)

S - saturation flow per lane in PCU's

## 4.0 Case Study

Dehiwela junction (Galle Road/Hill Street) is selected as a case study to illustrate the application of the proposed method. Data from a 13 hour traffic count carried out at the intersection were used as design flow inputs. Three different time periods to represent; peak flow, high right turn proportion and off peak flow are considered. Three alternate designs; isolated signal, normal roundabout and signalised roundabout, for each time period, are considered and the results are compared based on the expected delays.

Delays due to a signalised intersection is calculated using the formula developed based on shock wave theory [Gerlough & Huber (1975)] given below.

$$d = \frac{C^2 (1 - \lambda)^2}{2(1 - \frac{q}{s})}$$

Where,

$\lambda$ - ratio between effective green to cycle time

q - arrival rate of vehicle

s - departure rate of vehicle

d - mean delay per cycle per phase per lane

To estimate the delays at an roundabout, an emperical relationship given below [Kumarage et al, (1996)] is used.

$$d = \frac{51.2 \ (Q_e \ Q^2_c)^{0.2392}}{(W_e \ W^4_c)^{0.4116}}$$

Where,

$Q_e$ $Q_c$ - entry and circulating flow

$W_e$ $W_c$ - entry and circulating width

d - mean delay per vehicle

Delays at a signalised roundabout is calculated as a combination of above two delays (signal delay + roundabout delay).

The three periods considered are :

Period 1 - peak flow ; 7.15 - 7.30 a.m

Period 2 - when right turns are high ; 7.45 - 8.00 a.m

Period 3 - off peak flow ; 11.15 - 11.30 a.m

## 4.1 Geometric and Flow Information at Dehiwela Junction :

The intersection geometries given in Tables 2 and 3 and Figure 4 & 5 were considered for the analysis. The vehicle flows that were used for the respective calculations are given in Table 4.

**Table 2 : Geometric Information For a Signalised Intersection**

| | From Mt. Lavinia (App-1) | FromStation Roadc (App-2) | From Wellawatta (App-3) | From Hill Street (App-4) |
|---|---|---|---|---|
| No of Through Lanes | 2 | 1 | 2 | 1 |
| No of Right Turn Lanes | 1 | 1 | 1 | 1 |
| Approach width (m) | 12 | 9 | 12 | 9 |

**Table 3 : Geometric information for a roundabout**

| Approach | (U) Weaving section | (r) Entry Radius (meters) | Entry Angle (degree) | K | S | $X^2$ | M | $t_D$ | $f_c$ | F |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 4-1 | 10 | 42 | .90946 | 0 | 13.5 | .3679 | 1.3655 | 1.061 | 4090 |
| 2 | 1-2 | 25 | 42 | .96836 | 0 | 9.6 | .3679 | 1.3655 | 0.837 | 2908 |
| 3 | 2-3 | 16 | 42 | .94586 | 0 | | .3679 | 1.3655 | 1.009 | 3818 |
| | | | | | | 12.5 | | | | |
| 4 | 3-4 | 16 | 42 | .94586 | 0 | 8.6 | .3679 | 1.3655 | 0.780 | 2605 |

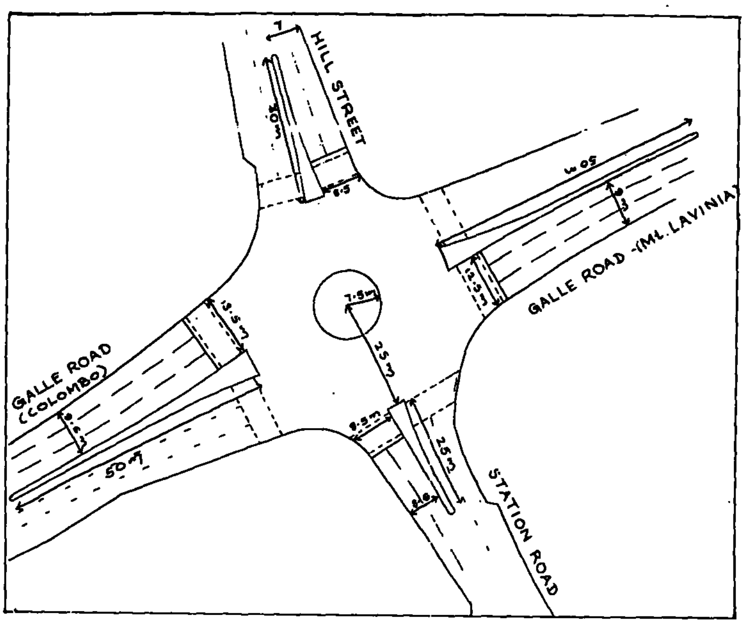


**Figure 4 : Geometry for a Signalised Roundabout**

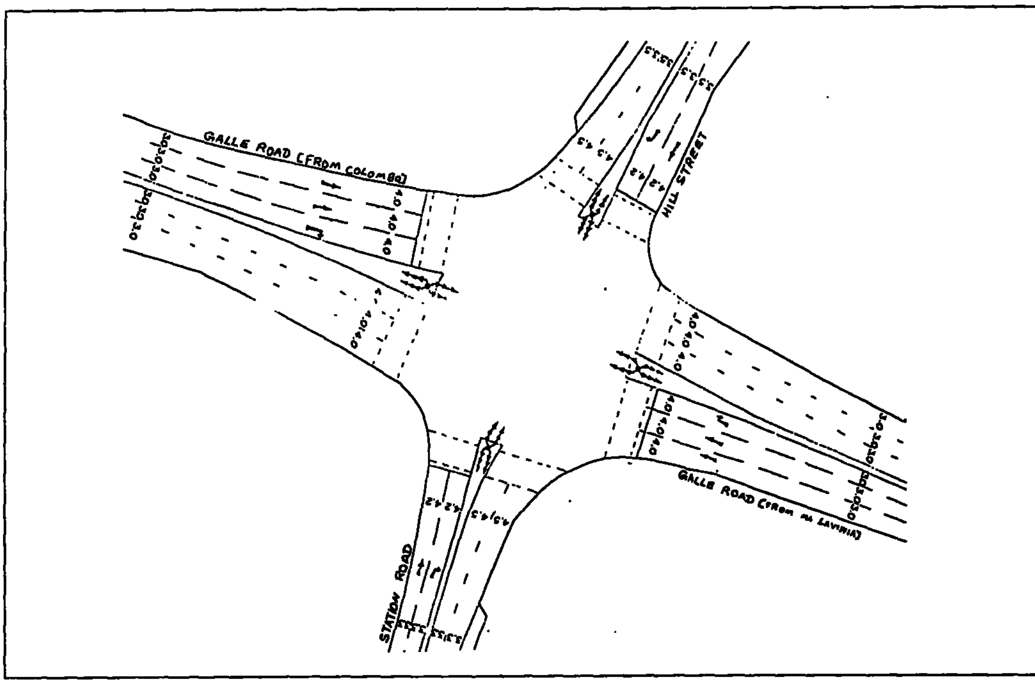


**Figure 5 : Geometry at Dehiwela Junction Signalised Intersection**

**Table 4 : Hourly Turning Movements**

| Approach | Movement | Peak (PCU) 7.15 - 7.30 | High R. Turns (PCU) 7.45 - 8.00 | Off Peak (PCU) 11.15 - 11.30 |
|---|---|---|---|---|
| From Mt. Lavinia (1) | Through - 1 | 1432 | 926 | 804 |
| | Through - 2 | 1432 | 926 | 804 |
| | R. Turn - 3 | 180 | 259 | 235 |
| From Station Road (2) | Through - 1 | 132 | 342 | 114 |
| | R. Turn - 3 | 40 | 57 | 34 |
| From Wellawatte (3) | Through - 1 | 593 | 609 | 742 |
| | Through - 2 | 593 | 609 | 742 |
| | R. Turn - 3 | 40 | 84 | 144 |
| From Hill Street (4) | Through - 1 | 140 | 554 | 272 |
| | R. Turn - 3 | 132 | 137 | 136 |

## 4.2 Timing for Signalised Intersection (Alternate 1)

Table 5 shows the optimum signal timing schemes for the three time periods if the intersection is to be controlled as a signalised intersection.

**Table 5 :Signal Timing for Signalised Intersection**

| | | Period 1 | Period 2 | Period 3 |
|---|---|---|---|---|
| No. of Phase | | 4 | 4 | 3 |
| Cycle Time (secs) | | 120* | 120 | 90 |
| Total Critical Lane Volume (TCL) | | 2045 | 1684 | 1380 |
| Green | Phase 1 - Galle Rd. Through | 80 | 57 | 46 |
| Times | Phase 2 - Galle Rd. Right turns | 10 | 17 | 14 |
| (Secs) | Phase 3 - Station Rd. | 7 | 9 | 18** |
| | Phase 4 - Hill Street | 7 | 21 | - |

* Saturated Condition

** both Station Road & Hill Street operate simultaneously

### 4.3 Capacities for Roundabout (Alternate 2)

The entry flow and entry capacities for a roundabout operation are given in Table 6.

**Table 6 : Roundabout Operation**

| Period | Approach | Circulating Flow | Entry Flow | Entry Capacity |
|---|---|---|---|---|
| 1 | 1 | 312 | 3044 | 3151 |
| | 2 | 3176 | 172 | 160* |
| | 3 | 352 | 1226 | 3188 |
| | 4 | 1306 | 272 | 1587 |
| 2 | 1 | 775 | 2111 | 2724 |
| | 2 | 2142 | 399 | 915 |
| | 3 | 658 | 1302 | 2900 |
| | 4 | 1359 | 691 | 1547 |
| 3 | 1 | 552 | 1843 | 2930 |
| | 2 | 1979 | 148 | 1035 |
| | 3 | 383 | 1627 | 3159 |
| | 4 | 1877 | 408 | 1154 |

* *flow exceeds capacity*

### 4.4 Timing and Capacity for signalised Roundabout (Alternate 3)

Table 7 shows the signal timing scheme and entry capacities if signalised roundabout is considered.

**Table 7 :Signalised Roundabout**

| Period | No. of Phase | Cycle Time | Green Time | | Approach | Circulating Flow | Entry Flow | Entry Capacity |
|---|---|---|---|---|---|---|---|---|
| | | | Phase 1 | Phase 2 | | | | |
| 1 | 2 | 45 | 33 | 4 | 1 | 40 | 3044 | 3402 |
| | | | | | 2 | 132 | 172 | 2383 |
| | | | | | 3 | 180 | 1226 | 3351 |
| | | | | | 4 | 40 | 272 | 2549 |
| 2 | 2 | 40 | 22 | 10 | 1 | 84 | 2111 | 3362 |
| | | | | | 2 | 137 | 399 | 2380 |
| | | | | | 3 | 259 | 1302 | 3276 |
| | | | | | 4 | 57 | 691 | 2536 |
| 3 | 2 | 30 | 16 | 6 | 1 | 144 | 1843 | 3306 |
| | | | | | 2 | 136 | 148 | 2380 |
| | | | | | 3 | 235 | 1627 | 3299 |
| | | | | | 4 | 34 | 408 | 2553 |

### 4.5 Comparison of Delays of Alternate Designs

Expected delays due to the three different control measures are given in Table 8 and Figure 6.

**Table 8 : Comparison of Expected Delays in veh.hrs./hr.**

| | Alternate 1 Fully Signalised | Alternate 2 Roundabout | Alternate 3 Signalised Roundabout |
|---|---|---|---|
| Delay in Period-1 | 65.7 | 50.43 | 28.1 |
| Delay in Period-2 | 56.1 | 65.4 | 35.7 |
| Delay in Period-3 | 26.2 | 46.4 | 25.8 |

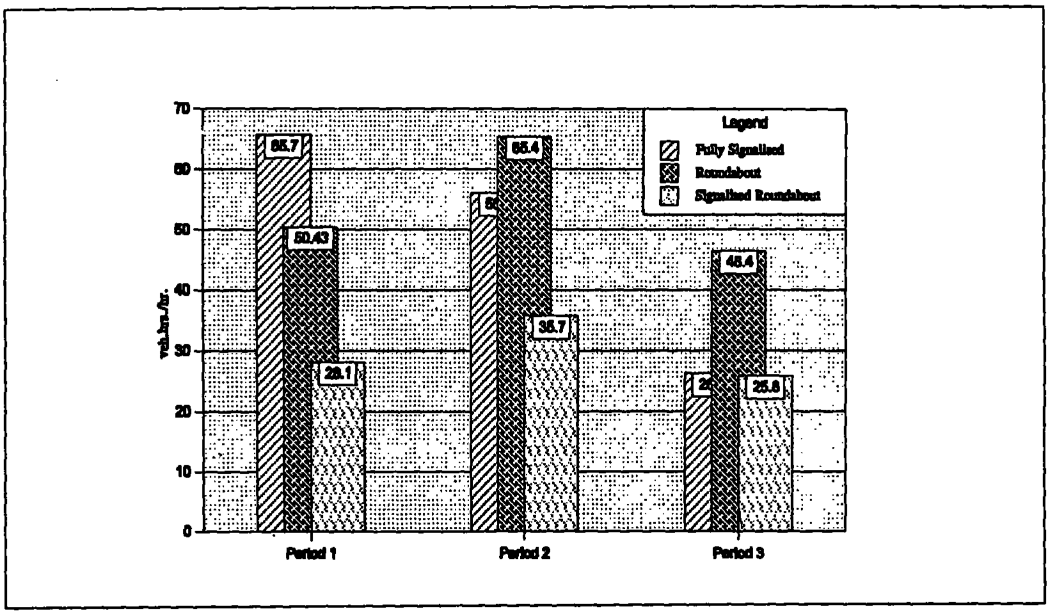


Figure 6 : Comparison of Expected Delays

## 5.0 Observation

The result indicate that it is necessary to have three or more phases if the intersection is to be controlled as a signalised intersection. The cycle time required for such an operation is about 90-120 sec. Further, it can be seen that the intersection can be over saturated during peak periods.

If a normal roundabout is used, it can be seen that entry flow during certain time periods exceed the entry capacity causing congestion. Further, it can be seen (Table 8) that the expected delay for vehicles at a roundabout is always more than that for a signalised roundabout for all 3 periods tested. This is due to the heavy imbalance in approach entry flows.

It can be seen that a signalised roundabout with two phase signal scheme is satisfactory for these conditions. The cycle time is around 30-45 secs. and does not vary significantly with time. A two vehicle length storage per lane is considered necessary for storing of left & right turning traffic on the Galle Road. This length may be reduced to one vehicle length for the other 2 minor arms.

With the up stream displacement of the pedestrian crossings, the intersection crossing length will increase, thus all-red-time would have to be increased.

## 6.0 Conclusion

It can be concluded that a signalised roundabout is a suitable alternative for intersection control at existing roundabouts, specially when right turning vehicles do not get sufficient gaps to clear the intersection. Gaps created due to signal phasing facilitate the movements from approaches with lesser flow.

However, signalised roundabouts are not recommended for places where there are no existing roundabouts. Signal control alone can be used for such locations as new roundabouts would require more space at the intersection.

It is necessary to conduct more research and monitoring to understand driver behaviour at signalised roundabouts, so that more efficient signal timing could be derived. The adequacy of the storage length will also depend on both driver & pedestrian behaviour. This could be verified & tested only after signalising an existing roundabout on a trial basis.

## 7.0 Acknowledgement

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