

Signal timing calculation methods for vehicle-actuated and fixed-time signals

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NOTES

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This digital copy includes some minor edits to the previously unpublished report.

In this report, discussions relevant to the Highway Capacity Manual (HCM) refers to the Third Edition of HCM.

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Reference

AKÇELİK, R. (1995). Signal Timing Calculation Methods for Vehicle-Actuated and Fixed-Time Signals. Working Paper WD TO 95/020. ARRB Transport Research Ltd, Vermont South, Australia.

Related Publications

AKÇELİK, R. (1994). Estimation of Green Times and Cycle Time for Vehicle-Actuated Signals. *Transportation Research Record* 1457, pp 63-72.

AKÇELİK, R. (1995). Signal Timing Analysis for Vehicle-Actuated Control. Working Paper WD TE 95/007. ARRB Transport Research Ltd, Vermont South, Australia.

AKÇELİK, R., CHUNG, E. and BESLEY, M. (1997). Recent research on actuated signal timing and performance evaluation and its application in SIDRA 5. *Compendium of Technical Papers, ITE 67th Annual Meeting*.

AKÇELİK, R., BESLEY, M. and CHUNG, E. (1998). An evaluation of SCATS Master Isolated control. Proceedings of the 19th ARRB Transport Research Conference (Transport 98) (CD), pp 1-24. ARRB Transport Research Ltd, Vermont South, Australia.

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SUMMARY

Recent research (Working Documents WD TE 95/007 and WD TO 95/013) has shown that degrees of saturation at actuated signals can be well below the value of 0.95 suggested in the US Highway Capacity Manual. Equal degrees of saturation do not necessarily result, and the minor movements may get lower degrees of saturation than the major movements, indicating inefficient operation. This report presents a simple method for calculating average cycle time and green times at actuated signals. The method makes use of a regression model for estimating degrees of saturation at actuated signals in order to utilise the *practical signal timing* method used for fixed-time signals.

The method can be implemented in SIDRA easily because it is consistent with the current method used for fixed-time signals. This will be useful since the implementation of the more comprehensive and detailed method described in WD TE 95/007 requires more major effort. Various aspects of implementation of the method in the SIDRA package are discussed.

The example given in this report demonstrates the finding from recent analytical and simulation studies that actuated signals are not as efficient as generally assumed. The cycle times can be reduced and the efficiency of the intersection can be improved by adopting EQUISAT and optimum cycle time policies. Reduced cycle times improve capacities of filter turns and short lanes, and reduce queue lengths. The distribution of delays between major and minor movements should also be paid attention as this is an important issue in terms of level of service.

Preliminary study of the SCATS Master Isolated control strategy indicates that improved efficiencies can be achieved by the SCATS algorithms over the traditional actuated signal control. This will be investigated by simulations and surveys at real-life intersections.

The results given in this report also show that the signal control strategy implied by the timing, capacity and performance analysis method is an important issue which should be addressed more closely in future research.

NOTATIONS AND BASIC RELATIONSHIPS

c	Cycle time (seconds) $c = r + g$
$c_{\min}$	Minimum cycle time (seconds)
$c_{\max}$	Maximum cycle time (second)
c_p	Practical cycle time: the cycle time calculated to achieve specified target degrees of saturation (x_p) and satisfy the minimum and maximum green time constraints (seconds)
d	Average delay per vehicle for all vehicles queued and unqueued (seconds)
d'	Average delay per vehicle for queued vehicles (seconds) $d' = d / p_q$ where p_q = proportion queued
D	Total (aggregate) delay (veh-h/h) $D = d q$ (where q is in veh/s)
e_h	Gap setting as a <i>headway</i> value (seconds)
e_s	Gap setting as a <i>space time</i> value as used with <i>presence</i> detection (seconds) $e_s = e_h - t_0$
G	Average displayed (controller) green time (seconds)
g	Average effective (movement) green time (seconds) $g = G - l_s + l_e$
$g_{\max}$	Effective maximum green time (seconds) $g_{\max} = G_{\max} - l_s + l_e$
$G_{\max}$	Maximum green setting as a controller (displayed) value (seconds)
$g_{\min}$	Effective minimum green time (seconds) $g_{\min} = G_{\min} - l_s + l_e$
$G_{\min}$	Minimum green setting as a controller (displayed) value (seconds)
g_p	Required green time (seconds) $g_p = u_p c = y c / x_p$ subject to $g_{\min} \leq g_p \leq g_{\max}$
g_p'	Adjusted required green time (seconds) $\begin{aligned} g_p' &= g_p && \text{if } g_{\min} \leq g_p \leq g_{\max} \\ g_p' &= g_{\min} && \text{if } g_p < g_{\min} \\ g_p' &= g_{\max} && \text{if } g_p > g_{\max} \end{aligned}$

I	Intergreen time (clearance time consisting of yellow and all-red time) (seconds) $I = t_y + t_{ar}$
I_s	Starting intergreen time (intergreen time that precedes the current green period) (seconds)
I_t	Terminating intergreen time (intergreen time that follows the current green period) (seconds)
l	Lost time for a movement (seconds) $l = I_s + l_s - l_e$
l_e	End gain for a movement, which is associated with the use of yellow interval, also including any <i>early cut-off time</i> as an additional end gain time (seconds)
l_s	Start loss for a movement, which is associated with driver reaction time and acceleration delays until the steady saturation flow rate is reached, also including any <i>late start time</i> as an additional start loss time (seconds)
L	Intersection lost time: sum of lost times for critical movements (seconds)
q	Flow rate (veh/s or veh/h); for the purpose of timing calculations, defined as the arrival (demand) flow rate, i.e. the average number of vehicles per unit time as measured at a point upstream of the back of queue
Q	Capacity (veh/s or veh/h): maximum arrival flow rate that can be serviced under prevailing flow conditions $Q = sg/c$
r	Average effective (movement) red time (seconds) $r = c - g$
R	Average displayed (controller) red time (seconds)
s	Saturation flow rate (veh/h or veh/s)
sg	Cycle capacity (veh) (s in veh/s, g in seconds)
t_{ar}	All-red time (seconds)
t_{max}	Maximum required movement time ($= g_{max} + l$)
t_{min}	Minimum required movement time ($= g_{min} + l$)
t_o	Detector occupancy time (seconds/veh): duration of the period when the detection zone is <i>occupied</i> by a vehicle
t_p	Required movement time (seconds) $t_p = g_p + l$ subject to $t_{min} \leq t_p \leq t_{max}$

t_y	Yellow time (duration of yellow interval) (seconds)
u	Green time ratio $u = g / c$
u_p	Required green time ratio (for $x = x_p$, equivalent to $x = x_a$ in the case of actuated signals) $u_p = y / x_p$
x	Degree of saturation, i.e. the ratio of arrival (demand) flow rate to capacity, equivalent to the ratio of arrivals per cycle ($q c$ vehicles) to the maximum number of vehicles that can depart per cycle (sg vehicles) $x = q / Q = (q c) / (sg)$
x_a	Degree of saturation for actuated signals (result of controller settings and demand flows)
x_p	Practical (target) degree of saturation for signal timing calculation purposes
y	Flow ratio, i.e. the ratio of average arrival flow rate during the signal cycle to the saturation flow rate $y = q / s$



1 INTRODUCTION

Recent research (Akçelik and Chung 1995; Akçelik 1995) has shown that, for traditional vehicle-actuated signals, degrees of saturation can be well below the value of 0.95 suggested in the US Highway Capacity Manual, equal degrees of saturation do not necessarily result, and the minor movements may get lower degrees of saturation than the major movements, indicating inefficient operation.

This report presents a simple method for calculating average green and cycle times at actuated signals, making use of estimates of degrees of saturation at actuated signals as target degrees of saturation in the practical cycle time and green split formulae. The method is consistent with the current Australian and USA (Highway Capacity Manual) methods for the analysis of fixed-time (pretimed) signals (Akçelik 1981, 1990; TRB 1994), and therefore easy to implement in the SIDRA package (Akçelik, Besley, et al 1995). The more comprehensive and detailed method for estimating actuated signal timings described in Akçelik (1995) could be implemented in a later version of SIDRA.

The notations and basic relationships are given at the start of the report for the symbols used in various formulae given in the report.

2. DEGREES OF SATURATION AT ACTUATED SIGNALS

Akçelik and Chung (1995) give the following regression model based on simulation data for estimating degrees of saturation at vehicle-actuated signals (x_a):

$$x_a = 0.8 y^{0.5} e_h^{-0.1} r^{0.18} \quad \text{subject to } 0.40 \leq x_a \leq 0.95 \quad (2.1)$$

where y is the flow ratio, e_h is the gap setting as a headway value (seconds) and r is the effective red time (seconds).

A simple method to determine average cycle time and green times at vehicle-actuated signals using the degree of saturation calculated from Equation (2.1) as a target degree of saturation is described in Section 3. The method requires iterative calculations, partly because of the red time variable in Equation (2.1). The following formula for use in initial calculations in the iterative process helps to reduce the number of iterations:

$$x_a = 1.5 y^{0.5} e_h^{-0.1} \quad \text{subject to } 0.40 \leq x_a \leq 0.95 \quad (2.2)$$

Degrees of saturation estimated from Equation (2.1) for various values of gap setting (e_h), effective red time (r) and flow ratio (y) are given in Table 2.1, and values for $e_h = 3.5$ s shown in Figure 2.1.

The US Highway Capacity Manual (TRB 1994, p. 9-103) states that "An actuated signal is assumed to be extremely efficient in the use of available green time. Thus, the average cycle length should be estimated using a high critical v/c ratio (degree of saturation) of approximately 0.95. ... Green times will be computed on the basis of a constant v/c ratio of 0.95 because it is assumed that the actuated signal assigns green time proportionally."

It is seen from the results given here that degrees of saturation at actuated signals can be well below the value of 0.95 suggested by the US Highway Capacity Manual, and the equal degree of saturation method implied by the HCM statement is not substantiated. In fact, actuated signals are seen to produce green splits that result in unequal degrees of saturation with lower degrees of saturation allocated to movements with low demand (low flow ratios). As a result of this, actuated signal cycle times tend to be longer than the cycle times obtained using the equal degree of saturation (EQUISAT) principle as shown through an example in Section 4. In practice, lower maximum green times and shorter gap settings are used for movements with low demand to overcome this inefficiency. However, this is not always possible due to variations in demand throughout the day. In any case, some inefficiencies in traditional actuated timings cannot be avoided as even the smallest possible gap setting (e_h) may give degrees of saturation well below 0.95.

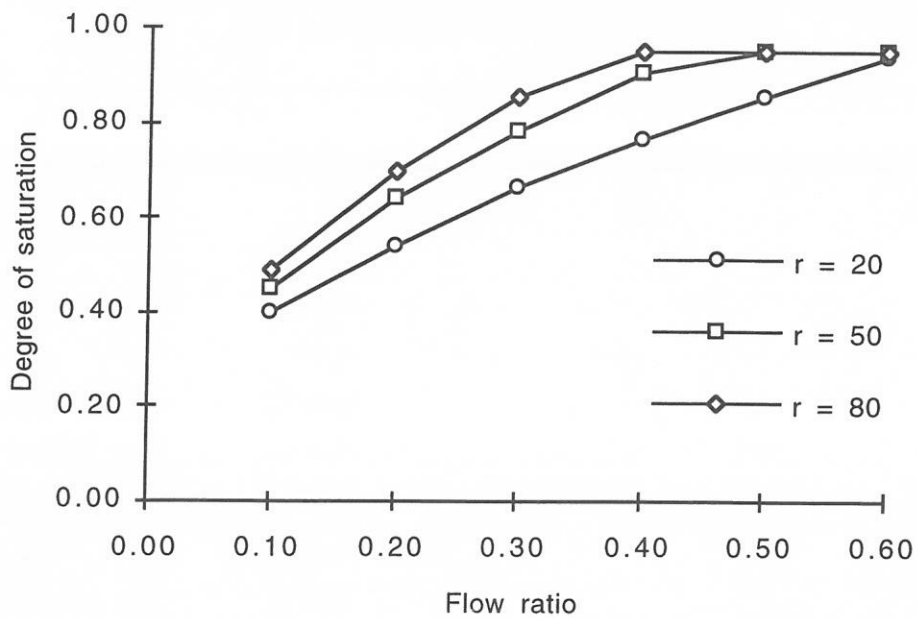


Fig. 2.1 – Degrees of saturation at vehicle-actuated signals estimated from *Equation 2.1* for various values of effective red time (r) and flow ratio (y) using a gap setting of $e_h = 3.5$ s

Table 2.1

***Typical values of degrees of saturation at actuated signals
calculated from Equation (2.1)***

e_h	r	y	x_a
3.0	20	0.1	0.40 (min)
		0.3	0.67
		0.5	0.87
	50	0.1	0.46
		0.3	0.79
		0.5	0.95 (max)
	80	0.1	0.50
		0.3	0.86
		0.5	0.95 (max)
3.5	20	0.1	0.40 (min)
		0.3	0.66
		0.5	0.86
	50	0.1	0.45
		0.3	0.78
		0.5	0.95 (max)
	80	0.1	0.49
		0.3	0.85
		0.5	0.95 (max)
4.0	20	0.1	0.40 (min)
		0.3	0.65
		0.5	0.84
	50	0.1	0.45
		0.3	0.77
		0.5	0.95 (max)
	80	0.1	0.48
		0.3	0.84
		0.5	0.95 (max)

3. A SIMPLE TIMING ESTIMATION METHOD FOR ACTUATED SIGNALS

As seen from *Equation (2.1)*, the degree of saturation, x_a , at actuated signals is a function of various controller settings as well as demand flows that determine the average green, red and cycle times (Akçelik 1995). In turn, x_a estimated from *Equation (2.1)* can be used to estimate actuated signal timings as an alternative to the more comprehensive and detailed method given in Akçelik (1995). For this purpose, the practical cycle and green time method used for fixed-time signals (Akçelik 1981, 1990) can be adopted setting the target degree of saturation as the actuated signal degree of saturation from *Equation (2.1)*:

$$x_p = x_a \quad (3.1)$$

While the use of a fixed value of x_p for all movements ($x_p = 0.9$ for fixed-time signals) results in equal degrees of saturation, the actuated signal method will yield unequal degrees of saturation since movements with lower flow ratios will receive longer green times (therefore lower degrees of saturation). This reflects the operation of traditional actuated signals, which is not necessarily optimal.

The required times resulting from the use of $x_p = x_a$ will be subject to minimum and maximum green time constraints as in the case of fixed-time signals. An iterative method will be required because of the red time variable in *Equation (2.1)* to estimate x_a . The degree of saturation from *Equation (2.2)* will be used to calculate initial timings. The formulae for the application of this method are given below.

Formulae for Estimating Signal Timings at Actuated Signals

The following formulae can be used for estimating the average green times and cycle time at actuated signals as well as for calculating signal timings for fixed-time signals based on the principle of equal degrees of saturation (EQUISAT). The method is also applicable to fixed-time signals with unequal degrees of saturation, or with green split priority to major road movements.

Various formulae given below are expressed in terms of critical movements. The ARR 123 (Akçelik 1981) method for determining critical movements is applicable using the required times based on the actuated signal degree of saturation.

1. Required green time ratio

The required green time ratio that will yield a degree of saturation equal to the target degree of saturation ($x = x_p$) is calculated from:

$$u_p = \frac{y}{x_p} \quad (3.2)$$

where

y = flow ratio, $y = q / s$ (q = arrival flow rate and s = saturation flow rate),

x_p = target degree of saturation ($x_p = x_a$ in the case of actuated signals).

2. Required movement time and critical movements

The *required movement time* is the sum of green time required to achieve the target degree of saturation (g_p) and the movement lost time, subject to minimum and maximum time constraints:

$$t_p = g_p + l \quad \text{subject to } t_{\min} \leq t_p \leq t_{\max} \quad (3.3)$$

$$g_p = u_p c = \frac{y c}{x_p} = \frac{q c}{s x_p} \quad (3.4)$$

$$\begin{aligned} g_p' &= g_p \text{ if } g_{\min} \leq g_p \leq g_{\max} \\ &= g_{\min} \text{ if } g_p < g_{\min} \\ &= g_{\max} \text{ if } g_p > g_{\max} \end{aligned} \quad (3.4a)$$

$$l = I_s + t_s - t_e \quad (3.5)$$

where

t_p = required movement time

g_p = original required green time

g_p' = adjusted required green time

c = cycle time

l = lost time

I_s = movement (starting) intergreen time

t_s = start loss

t_e = end gain

$t_{\min}$ = minimum required movement time ($= g_{\min} + l$)

$t_{\max}$ = maximum required movement time ($= g_{\max} + l$)

$g_{\min}$ = minimum effective green time

$g_{\max}$ = maximum effective green time

The first step in determining critical movements is to compare the required time values of movements sharing the same phase. For each phase, or combination of phases, the movement with the largest required time is chosen and the others are eliminated. The second step is to consider possible movement combinations (paths) which complete one signal cycle, to sum up the required movement times for each path, and to choose the path with the largest total required time. This is the critical path, and the movements in this path are the critical movements. Refer to report ARR No. 123 (Akçelik 1981) for more detailed information on the critical movement identification method.

Equation (3.4) shows that the required green times depend on cycle time. The dependence of required green times on cycle time reflects what happens in real life, i.e. longer green times are needed to achieve the same degree of saturation if cycle time is longer. This is because longer cycle times mean longer red times, and hence, longer queues to clear. Expressing this in terms of *Equation (3.4)*, a longer cycle time means that more vehicles arrive during one cycle ($q \cdot c$ vehicles) and a longer green time is required to meet this demand. For actuated signals, the target degree of saturation based on *Equation (2.1)*, $x_p = x_a$, will be low for minor movements, and therefore the required green time will be longer compared with the use of $x_p = 0.9$ for fixed time signals. This results in longer cycle times for the actuated signal case, especially due to additional factors like reduced saturation flows under longer cycle times.

3. Cycle time

For cycle time calculations, the total intersection lost time (L) and total required green time ratio (U_p) for the *intersection* are calculated as the sums of corresponding values (l , u_p) for critical movements:

$$\begin{aligned} L &= \sum l \quad \text{and} \\ U_p &= \sum u_p \end{aligned} \tag{3.6}$$

However, it is necessary to calculate adjusted values of L and U_p (L' and U_p') in order to allow for critical movements with required times set equal to the minimum or maximum green time:

$$\begin{aligned} L' &= L + G_m \\ G_m &= \sum g_p' \quad \text{for movements with } g_p' \neq g_p \\ U_p' &= \sum u_p \quad \text{for movements with } g_p' = g_p \end{aligned} \tag{3.7}$$

where G_m is the sum of $g_{\min}$ or $g_{\max}$ values of the critical movements whose required green times are set to $g_p' = g_{\min}$ or $g_p' = g_{\max}$, therefore not included in the summation for $U_p' = \sum u_p = \sum (y / x_p)$.

If no critical movements have required green times that are set to $g_p' = g_{\min}$ or $g_p' = g_{\max}$ (i.e. all movements have $g_p' = g_p = y / x_p$), then $L' = L$ and $U_p' = U_p$.

Using these values, the *practical cycle time*, c_p , is calculated from:

$$c_p = \frac{L'}{1 - U_p'} \quad \text{subject to } U_p' < 1.0 \quad (3.8)$$

For fixed-time signals, minimum and maximum cycle time constraints can be used, $c_{\min} \leq c_p \leq c_{\max}$. For actuated signals, the method will give $c_p = c_{\min}$ when all critical movements have $g_p' = g_{\min}$, or $c_p = c_{\max}$ when all critical movements have $g_p' = g_{\max}$.

Need for iterative calculations

The above calculations need to be performed in an *iterative* way for several reasons:

- (i) the required green time (g_p) depends on the cycle time,
- (ii) saturation flow used in the calculation of flow ratio (y) depends on green and red times in the case of opposed turns, short lanes and lane blockages in shared lanes,
- (iii) the target degree of saturation in the case of actuated signals depends on red time (also on y), and
- (iv) lost time in the case of opposed turns depends on green and red times (also affected by opposing movement saturation flows).

In SIDRA, initial values of cycle time, saturation flow and opposed turn lost time are assumed for the iterative process. Similarly, various stopping conditions are used to end the iterative process (comparing effective green times and degrees of saturation between the last and previous iterations).

In the case of actuated signals, initial values of the target degree of saturation, $x_p = x_a$, can be calculated from *Equation (2.2)*.

In perfect equilibrium and working with real numbers, the value of practical cycle time would be equal to the sum of the required movement times for critical movements, and the green time allocated to each critical movement would be equal to the required green time: $c_p = T = \sum t_p$ and $g = g_p'$, therefore $c_p = L + \sum g_p'$. However, these equalities may not be realised due to various reasons, and the *chosen cycle time* may differ from the practical cycle time ($c \neq c_p$) and the resulting green times may not equal the required green times ($g \neq g_p'$). As a result of these differences, the degrees of saturation for critical movements differ from the target degrees of saturation. This is also the case for critical movements with green times set to $g_p' = g_{\min}$ or $g_p' = g_{\max}$ and for non-critical movements that receive longer green times than required.

In SIDRA, the chosen cycle time determined at the end of iterative process may differ from the practical cycle time because of rounding up in accordance with the *cycle increment* (default = 10 s for fixed time signals, 1 s for actuated signals) as well as the use of a moving average of the practical cycle times found at the end of successive iterations (to help with settling of results). The cycle time in the *i*th iteration is calculated as follows. The average cycle time is calculated from:

$$c_{av} = \frac{c_{i-1} + 3 c_p}{4} \quad (3.9)$$

where c_{i-1} is the cycle time found in the previous iteration and c_p is the practical cycle time calculated in the current (*i*th) iteration. The new cycle time to be used for the current iteration, c_i , is found by rounding up c_{av} according to the cycle time increment. The chosen cycle time, c equals c_i found in the final iteration.

4. Green times

Green times for individual movements need to be determined because they may differ from the required green times as discussed above, or the cycle time may be specified as given and the problem is to determine green splits. The method given below is consistent with the practical cycle time calculation method as it distributes the total available green time in proportion to the required green times. For the extension of the method to the case of *green split priority*, see Akçelik (1990).

For a given cycle time, c , the green times for critical movements can be calculated as follows. First, calculate all green times from

$$g = \frac{(c - L)}{\sum g_p} g_p \quad (3.9)$$

where the summation is for all critical movements.

Check the resulting green time, g , for each critical movements and :

$$\begin{aligned} \text{If } g < g_{\min}, \text{ set } g &= g_{\min} \\ \text{If } g > g_{\max}, \text{ set } g &= g_{\max} \end{aligned} \quad (3.10)$$

If *Equation (3.10)* is applied, i.e. if the green time for any critical movement is set to its minimum or maximum value, add all such green times to the intersection lost time to calculate an adjusted total lost time:

$$L' = L + \sum (g_{\min} + g_{\max}) \quad (3.11)$$

and then recalculate green times for other movements from

$$g = \frac{(c - L')}{\sum g_p} g_p \quad (3.12)$$

where the summation excludes the critical movements with $g = g_{\min}$ and $g = g_{\max}$.

An important implication of this method is that the movements with $g_p' = g_{\min}$ are not always allocated $g = g_{\min}$, but may be allocated longer green times, $g > g_{\min}$ in order to achieve more balanced degrees of saturation.

Once the green times for critical movements have been determined, the green times for non-critical movements are determined by applying the same method to sub-cycles formed by critical movements with paths matching the critical movements.

4. EXAMPLE

The signal timing method described in the previous section has been applied to the simple example shown in *Figure 4.1*. A simple two-phase case is considered with a single movement in each phase. This occurs at the intersection of two one-way streets with single lanes. Saturation flows are equal and given as $s = 1800$ veh/h. Approach flows are unequal and the average flow rates for the total flow period (one hour) are given as $q_1 = 342$ veh/h (minor road) and $q_2 = 954$ veh/h (major road). A simple peak demand pattern is assumed as shown in *Figure 4.1* (Peak Flow Factor = 0.90). Arrival flow rates for the peak half hour and non-peak half hour periods are calculated accordingly. The displayed and effective green and red times are equal. Thus, lost times equal intergreen times ($l = I = 5$ s for both movements). Minimum green times are equal for both movements ($G_{\min} = 8$ s). The maximum green times are $G_{\max 1} = 40$ s and $G_{\max 2} = 70$ s. The gap settings (as headway values) are $e_{h1} = 2.5$ s and $e_{h2} = 3.5$ s.

The signal timings for the peak and non-peak half hour periods are calculated according to three different methods:

- (i) actuated signals with cycle time determined using the practical cycle time method (*Equation 3.8*) and green splits determined using *Equations (3.9) to (3.12)* with $x_p = x_a$ from *Equations (2.1) and (2.2)*;
- (ii) fixed-time signals with cycle time determined using the practical cycle time method (*Equation 3.8*) and green splits determined according to the principle of equal degrees of saturation (EQUISAT) using *Equations (3.9) to (3.12)* with $x_p = 0.9$ for both movements;
- (iii) fixed-time signals with optimum (minimum total delay) cycle time determined using the variable cycle time facility of SIDRA and green splits determined according to the EQUISAT principle as in (ii).

The cycle increment is 1 s in all cases (used for rounding the cycle time and green time results, and as the step size in optimum cycle search).

Delays are calculated for the peak and non-peak half hour periods using signal timings from (i) to (iii). Delay results for actuated and fixed-time signals are based on the formulae given in Akçelik and Chung (1995). For the purpose of this example, geometric delays to turning vehicles are not included in the delay analysis.

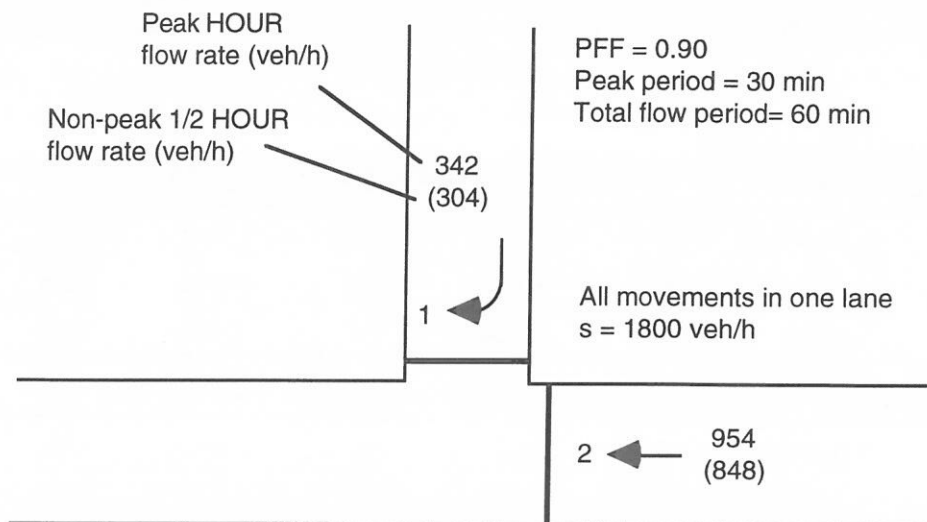
A delay evaluation is carried out by obtaining average delays for the total flow period according to the following control scenarios:

- (i) Actuated signals:
signal timings calculated using method (i) for the peak and non-peak half hour periods applied in respective half hour periods.

- (ii-A) Fixed-time signals with EQUISAT cycle and splits:
signal timings calculated using method (ii) for the peak half hour period applied *throughout the total flow period* (i.e. during both non-peak and peak half hour periods);
- (ii-B) Fixed-time signals with EQUISAT cycle and splits:
signal timings calculated using method (ii) for the peak and non-peak half hour periods applied in *respective half hour periods*;
- (iii-A) Fixed-time signals with OPTIMUM cycle and EQUISAT splits:
signal timings calculated using method (iii) for the peak half hour period applied *throughout the total flow period*;
- (iii-B) Fixed-time signals with OPTIMUM cycle and EQUISAT splits:
signal timings calculated using method (iii) for the peak and non-peak half hour periods applied in *respective half hour periods*;

The results are given in *Tables 4.1* to *Tables 4.3*. Notations in these tables are:

q	arrival flow rate (veh/h) during the flow period under consideration (in <i>Table 4.3</i> , q is the total intersection flow)
y	flow ratio ($y = q / s$)
x_p	target degree of saturation
x	resulting degree of saturation
X	intersection degree of saturation (highest x for any movement)
g	green time (seconds)
c	cycle time (seconds)
d	average delay per vehicle for all vehicles queued and unqueued (seconds)
d'	average delay per vehicle for queued vehicles as a measure of delay equity among competing movements (seconds) (in <i>Table 4.3</i> , d' for the intersection is the highest d' value for any movement, which is the minor movement value in this example)
D	total (aggregate) intersection delay as a measure of efficiency (vehicle- hours per hour)



SIGNAL PHASING

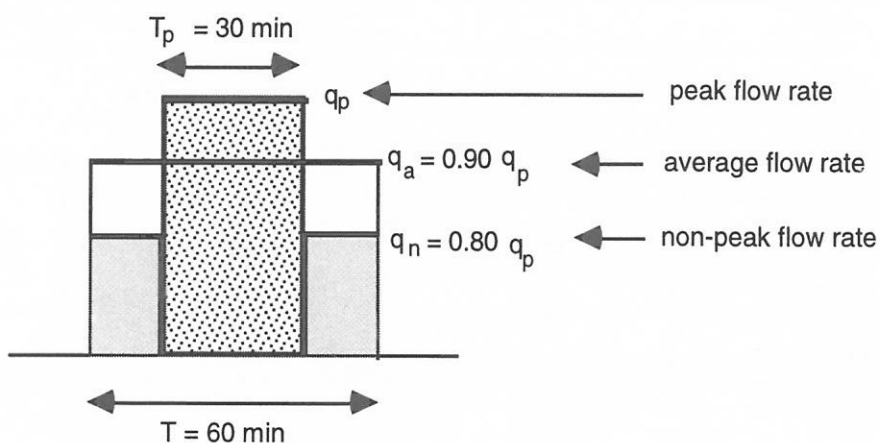
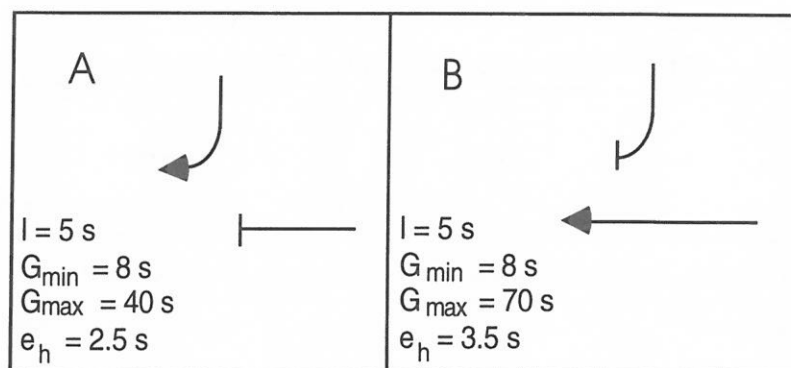


Fig. 4.1 – Example for calculation of actuated and fixed-time signal timings

Table 4.1

**Signal timings and delays for actuated and fixed-time signals:
results for peak half hour and non-peak half hour periods
(an example)**

(i) ACTUATED signals**PEAK HALF HOUR:** $c = 110$ (Intersection $d = 36.6$ s, $D = 14.65$ veh-h/h)

Mov	q (veh/h)	y	x_p	g (s)	x	d (s)	d' (s)
1	380	0.211	0.735	32	0.726	39.6	42.3
2	1060	0.589	0.950	68	0.953	35.6	35.6

NON-PEAK HALF HOUR: $c = 58$ (Intersection $d = 15.8$ s, $D = 5.05$ veh-h/h)

Mov	q (veh/h)	y	x_p	g	x	d	d' (s)
1	304	0.169	0.585	17	0.576	20.2	22.9
2	848	0.471	0.875	31	0.881	14.2	15.2

(ii) FIXED-TIME signals with EQUISAT cycle and splits**PEAK HALF HOUR:** $c = 91$ (Intersection $d = 33.5$ s, $D = 13.38$ veh-h/h)

Mov	q (veh/h)	y	x_p	g (s)	x	d (s)	d' (s)
1	380	0.211	0.90	22	0.873	46.2	46.2
2	1060	0.589	0.90	59	0.908	28.9	31.0

NON-PEAK HALF HOUR: $c = 39$ (Intersection $d = 19.3$ s, $D = 6.16$ veh-h/h)

Mov	q (veh/h)	y	x_p	g (s)	x	d (s)	d' (s)
1	304	0.169	0.90	8 (min)	0.823	21.5	21.5
2	848	0.471	0.90	21	0.875	18.5	19.7

(iii) FIXED-TIME signals with OPTIMUM cycle and EQUISAT splits**PEAK HALF HOUR:** $c = 105$ (Intersection $d = 31.0$ s, $D = 12.40$ veh-h/h)

Mov	q (veh/h)	y	x_p	g (s)	x	d (s)	d' (s)
1	380	0.211	0.90	25	0.887	53.9	53.9
2	1060	0.589	0.90	70	0.883	22.8	25.8

NON-PEAK HALF HOUR: $c = 64$ (Intersection $d = 15.1$ s, $D = 4.84$ veh-h/h)

Mov	q (veh/h)	y	x_p	g (s)	x	d (s)	d' (s)
1	304	0.169	0.90	14	0.772	29.3	29.4
2	848	0.471	0.90	40	0.754	10.0	13.0

Table 4.2

Delay results for the case when fixed-time signal plans calculated for the peak half hour period are applied to the non-peak half hour (an example)

FIXED-TIME signal timings with EQUISAT cycle and splits calculated for PEAK HALF HOUR (method ii) applied to NON-PEAK HALF HOUR

c = 91 (Intersection d = 17.7 s, D = 5.67 veh-h/h)

Mov	q (veh/h)	y	x _p	g (s)	x	d (s)	d' (s)
1	304	0.169	0.90	22	0.699	35.5	36.6
2	848	0.471	0.90	59	0.727	11.4	15.8

FIXED-TIME signal timings with OPTIMUM cycle and EQUISAT splits calculated for PEAK HALF HOUR (method iii) applied to NON-PEAK HALF HOUR

c = 105 (Intersection d = 19.4 s, D = 6.22 veh-h/h)

Mov	q (veh/h)	y	x _p	g (s)	x	d (s)	d' (s)
1	304	0.169	0.90	25	0.709	41.0	42.1
2	848	0.471	0.90	70	0.707	11.7	17.1

Table 4.3

Comparison of delays during the total flow period (one hour) at actuated and fixed-time signals under various control scenarios (an example)

(i) ACTUATED signals

Period	q (veh/h)	c (s)	X	D (veh-h/h)	d (s)	d' (s)
Peak half hour	1440	110	0.953	14.65	36.6	42.3
Non-peak half hour	1152	58	0.881	5.05	15.8	22.9
Total flow period	1296	—	—	9.85	27.4	42.3

**(ii-A) FIXED-TIME signals (EQUISAT cycle and splits)
peak half hour timing plan applied to non-peak half hour period as well**

Period	q (veh/h)	c (s)	X	D (veh-h/h)	d (s)	d' (s)
Peak half hour	1440	91	0.908	13.38	33.5	46.2
Non-peak half hour	1152	91	0.727	5.67	17.7	36.6
Total flow period	1296	—	—	9.53	26.5	46.2

**(ii-B) FIXED-TIME signals (EQUISAT cycle and splits)
separate signal timing plans for the peak and non-peak half hour periods**

Period	q (veh/h)	c (s)	X	D (veh-h/h)	d (s)	d' (s)
Peak half hour	1440	91	0.908	13.38	33.5	46.2
Non-peak half hour	1152	39	0.875	6.16	19.3	21.5
Total flow period	1296	—	—	9.77	27.1	46.2

**(iii-A) FIXED-TIME signals (OPTIMUM cycle and EQUISAT splits):
peak half hour timing plan applied to non-peak half hour period as well**

Period	q (veh/h)	c (s)	X	D (veh-h/h)	d (s)	d' (s)
Peak half hour	1440	105	0.887	12.40	31.0	53.9
Non-peak half hour	1152	105	0.709	6.22	19.4	42.1
Total flow period	1296	—	—	9.31	25.9	53.9

**(iii-B) FIXED-TIME signals (OPTIMUM cycle and EQUISAT splits):
separate signal timing plans for the peak and non-peak half hour periods**

Period	q (veh/h)	c (s)	X	D (veh-h/h)	d (s)	d' (s)
Peak half hour	1440	105	0.887	12.40	31.0	53.9
Non-peak half hour	1152	64	0.772	4.84	15.1	29.4
Total flow period	1296	—	—	8.62	23.9	53.9

Discussion

The results given in *Tables 4.1 to 4.3* demonstrate that, as argued in previous sections, actuated signals are not as efficient as generally assumed. It is seen that cycle times can be reduced and the efficiency of the intersection can be improved by adopting EQUISAT and optimum cycle time policies. Reduced cycle times have additional benefits of improved capacity for filter turns and short lanes, and reduced queue lengths.

On the other hand, actuated signals tend to favour minor movements to some degree, and could be more equitable as seen from the results for this example. This will be a factor to consider in the HCM method that places much emphasis on levels of service based on individual movement delays.

More complicated real-life intersection cases need to be analysed before firm conclusions can be drawn about such issues.

5. IMPLEMENTATION IN SIDRA

The simple method given here for calculating the cycle time and green times at actuated signals can be implemented in SIDRA easily because it is consistent with the current method used for fixed-time signals. This will be useful since the implementation of the more comprehensive and detailed method (Akçelik 1995) requires more major effort.

It is intended that the gap and maximum green time settings for use in SIDRA are set as global default values stored in the SIDRA configuration file as follows (standard default values shown for Drive rule = Left-hand side of the road):

Movements	Gap setting e_h	Max. green setting G_{max}
Through and left-turn	3.5 s	60 s
Fully controlled right-turn	2.5 s	30 s

In the case of permitted (filter) turns in shared or exclusive lanes, G_{max} and e_h values of the through movement will be used. In the case of permitted and protected turns (filter turn and green arrow), G_{max} and e_h values of the through movement will be used for the permitted (filter) turn period. These cases need further investigation.

The existing data structure of SIDRA allows maximum green times to be specified for each movement. Such values would override the global default values of G_{max} . For permitted (filter) turns, through movement G_{max} values will be used as stated above.

Other suggestions for implementation of the actuated signal timing method in SIDRA are as follows:

- (i) For the purpose of calculating spare capacities, a target degree of saturation $x_p = 0.95$ would be appropriate for actuated signals.
- (ii) For actuated signals, the cycle time increment will be forced to 1 s.
- (iii) The maximum cycle time specified by the user will be ignored. Any green split priority specification will also be ignored. These are not considered to be relevant to isolated actuated signal timing calculations.
- (iv) For coordinated actuated signals, the fixed-time signal timing method will be applied using user-specified practical degrees of saturation, x_p (maximum cycle time and green split priority specifications will apply).

- (v) The variable cycle-time facility will be allowed, with actuated signal degrees of saturation used for green split purposes only. The same will apply to user-specified cycle time. This may help with determining appropriate maximum green time settings.
- (vi) Green time constraint for short lanes will be allowed. The maximum green time that may have been calculated by the short lane model of SIDRA will be used in the calculations.
- (vii) For movements with two green periods, e.g. opposed and unopposed (permitted-protected) phasing, the opposed (permitted, filter turn) period is treated by SIDRA as undetected. The required time for the unopposed (protected, green arrow) period of such a movement is calculated by decreasing the demand for green time according to the green time provided in the opposed period (as a consequence of green times allocated to other movements). This method is applied generally to any movement which is critical in one green period and non-critical in the other green period. Furthermore, SIDRA critical movement algorithms use a complex method to balance the required times between the two green periods for a given movement, and between several movements with two green periods that may overlap. These methods will remain unchanged until more detailed analyses of their implications for actuated signals are carried out.
- (viii) For pedestrian movements at an intersection, and all movements generally, the probability of no arrivals during the duration of average cycle time will be calculated and the minimum green time will be reduced by this amount in order to allow for occasional phase calls under low demand conditions. The method is described in Akçelik (1995). In the example given in this report, this effect is ignored.
- (ix) For semi-actuated signals, as well as vehicle-actuated pedestrian crossings, special methods described in Akçelik (1995) will be adopted in due course.

6. CONCLUDING REMARKS

The example given in this report demonstrates the finding from recent analytical and simulation studies that actuated signals are not as efficient as generally assumed.

The cycle times can be reduced and the efficiency of the intersection can be improved by adopting EQUISAT and optimum cycle time policies. Reduced cycle times improve capacities of filter turns and short lanes, and reduce queue lengths. The distribution of delays between major and minor movements will also be paid attention as this is an important issue in terms of level of service.

The current ARRB research on SCATS Master Isolated control strategy indicates that such efficiencies can be achieved by the SCATS algorithms. This will be investigated by simulations and surveys at real-life intersections.

The results given in this report show that the signal control strategy implied by the timing, capacity and performance analysis method is an important issue. This will need to be addressed more closely in future research work.

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