□ 論 文 □

# Adaptive Signal Control for Oversaturated Arterials

과포화 간선도로의 실시간 신호처리

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요 약

교통수요가 용량보다 많아지면 신호교차로가 모든 교통량을 통과시키지 못하므로 시간이 갈수록 대기 행렬이 점점 길어질 것이다. 이러한 과포화상태에서는 늘어나는 대기 행렬을 조절하지 못하면 결국에는 Spillback이 상류 교차로로 확대되어 최악에는 교차로에서의 모든 방향의 움직임을 정지시키는 Gridlock상태로까지 악화 될 수 있다. 따라서 과포화 상태에서는 비포화 상태와는 달리 늘어나는 대기 행렬을 조절하여 통과 교통량을 최대화 시키는 것이 신호처리의 목적 함수가 될 수 있을 것이다.

6월호의 논문에서는 Static 한 상태의 과포화 간선도로를 신호처리에 의해 일정한 대기행렬을 유지하므로써 시스템을 최적화 하는 알고리즘을 개발하였다. 그러나 과포화 간선도로의 교통수요는 매 Cycle 마다 Dynamic 하게 변하고, 과포화의 교통상황에서는 미미한 교통 변화가 우리가 염려하는 Spillback 을 야기시킬 수 있기 때문에 본 논문에서는 6월호에서 개발한 알고리즘에 기초하여 실시간으로 신호처리 하는 알고리즘을 개발하였다.

과포화 상태의 5 개의 신호교차로를 가진 간선도로를 Simulation 하여 비교한 결과 본 논문에서 개발한 알고리즘이 PASSER II 나 TRANSYT 7F 보다 차량 한 대당 평균 운행시간이 각각 30 %, 20 % 줄어들었다.

## 1. INTRODUCTION

When volumes become excessively high, most of the present concepts of traffic signal optimization appear ineffective or invalid because they deal only with undersaturated traffic conditions. The control policy for oversaturated conditions should be different than that of undersaturated conditions because traffic phenomena between two conditions are totally different.

The previous paper presented in a Journal of Korean society of Transportation Vol. 15, No. 2, 1997 by author has shown a new signal optimization method for oversaturated arterials with two-way, multi-phase, left-turn operations (1). This paper further developed the previous one for the real-time purpose. Under oversaturated conditions, excess of demand of relative to capacity produces standing queues which grow over time and can exhaust the storage capacity of the approach. Uncontrolled queue growth can physically block intersection, degrade the queue discharge process thereby reducing service rates and spread over a large portion of the system. This process impacts traffic on other approaches which may even be nominally undersaturated, radically reducing the productivity of the system and potentially causing gridlock. Under these circumstances, the concept of minimizing delay and stops is subordinate to the goal of maximizing productivity.

The goal of IMPOST (Internal Metering Policy to Optimize Signal Timing) developed in the previous paper is to manage the growth of queues to maximize the productivity of the roadway system: to service as many vehicles as possible in a given period of time. IMPOST takes traffic network data, formulates the problem as a mixed integer linear program (10), solves the formulated problem and interfaces with WATSim (Wide-Area Traffic Simulator) (7) to apply real-time signal operation.

In real-time traffic conditions, however, there exist the traffic fluctuations each cycle. Eventhough arterial traffic volumes are metered, the turning-in and turning-out volumes vary every cycle. Since the small change of traffic could affect intersection spillback under oversaturated conditions, it is necessary to control traffic by real-time basis. It was therefore decided to develop a adaptive signal control policy based on a methodology developed in the previous paper.

The IMPOST formulation is particularly well suited for real-time implementation because the only thing to do is to keep maintaining optimal queues (6). The major requirement for the real-time application of IMPOST is an accurate and reliable estimate of the actual queue length on each approach at the beginning of the green phase. Green time need only be changed by adjusting end of green interval to keep optimal signal offsets when the actual queue threatens to either produce starvation or spillbaack.

To assess system performance on the basis of traditional traffic network performance measures, optimal signal settings derived in IMPOST, PASSER II (8) and TRANSYT 7F (9) were entered into the WATSim model. The results show that the signal setting of IMPOST takes 30 percent and 20 percent less travel time per vehicle than that of PASSER II and TRANSYT 7F, respectively, under oversaturated 5 intersection arterial.

## 2. LITERATURE REVIEW

### 2.1 Arterial Optimization Programs

#### 2.1.1 TRANSYT

TRANSYT is of one the most widely used models for signal timing in the United States and Europe. It is based on the dispersion of a vehicle platoon departing from a signalized intersection. It is a macroscopic deterministic model used to simulate and optimize signal timing on coordinated arterials and network. It uses the gradient search technique as the optimization algorithm. The gradient search technique uses a hill-climbing optimization method to minimize the performance index of the weighed amount of total delay and stops.

#### 2.1.2 PASSER

PASSER is a macroscopic optimization model. It has two functions, evaluation of an isolated intersection or optimization of the progression signal timing. The PASSER model maximizes total two-way progression bandwidth efficiency. This model sequentially evaluates cycle length, phase sequence and offsets which maximize the progression bandwidth and reduce delay. The model allows for variations in the overall progression speed and weighing of the directional bandwidth.

### 2.2 Adaptive Signal Control

#### 2.2.1 SCOOT (Split Cycle and Offset Optimization Technique)

Since 1973 the U.K. Transport and Road Research Laboratory has been researching SCOOT and a full-scale trial of SCOOT was carried out in Glasgow in 1979. Inductive loop detectors are located on the approaches to all signalized intersections which are under SCOOT control. The detectors are positioned as far upstream as possible from the stop-line. Based on detector measurements upstream of the intersection, the SCOOT traffic model computes the cyclic flow profile for every link every four seconds. SCOOT projects these profiles to the downstream intersection using the TRANSYT dispersion model.

For each link, the SCOOT predicts the current value of the queue at the stop-line. The detected vehicle is assumed to travel at a fixed cruise speed to the stop-line. The state of the lights is known, and using a preset saturation flow value, the length of the queue and the back of the queue is estimated. The position of the back of the queue is used to provide congestion information for the signal optimizer.

The SCOOT has a set of signal timings, if unaltered by the optimizer, would effectively be a fixed-time plan. By frequent small alterations, SCOOT controls the signals on a plan that evolves through time.

A few seconds before each stage change, the split optimizer estimates whether it is better to make the change earlier, as scheduled, or later. The split optimizer implements whichever alteration will minimize the maximum degree saturation.

The offset optimizer operates on each intersection, each cycle. The information in the cyclic flow profiles is used to estimate whether or not an alteration to the offset will improve the overall traffic progressions. A performance index using delay, stops and congestion is minimized. The SCOOT operates sub-areas of signals on a common cycle in order to maintain coordination between signals. The cycle time optimizer can vary the cycle of each sub-area in increments of a few seconds at intervals of not less than two to five minutes. Each sub-area is varied independently of other sub-areas between preset upper and lower bounds. The cycle time is varied to ensure that the most heavily loaded intersection operates, if possible, at a maximum degree of saturation of 90 percent. The cycle time of the sub-area may be changed where SCOOT calculates that, with alteration between single and double cycle operation, a net savings in delay is possible.

The amount of congestion, measured in the model for each link, is used to modify the decisions of the split and offset optimizers. The green time can be increased to reduce congestion, and the offset on a link can be improved to reduce the risk of blocking the upstream intersection.

### 2.2.2 SCATS (Sydney Co-ordinated Adaptive Traffic System)

The SCATS strategy was developed by Sims of the Department of Main Roads, New South Wales, Australia since 1979. It uses a hierarchical control architecture. At the local level, each subsystem makes independent decisions on its timing parameters on the basis of the degree of saturation in the subsystem. It uses information from vehicle detector, located in each lane immediately in advance of the stopline to adjust signal timing in response to variations in traffic demand and system capacity. Adjacent subsystems "marry" and get coordinated by a higher-level regional computer when their cycle times are equal or nearly equal. Likewise, when the degrees of saturation and the consequent desired cycle lengths become different, the two subsystems "divorce".

The common cycle time is updated every cycle in steps of up to six seconds according to the degree of saturation (DS) of that subsystem. The DS is measured using detectors located at stop-lines. Four phase split plans which express green times plus intergreens as percentages of the current cycle time are available at each intersection within a subsystem. Various VA (Vehicle Actuated) intersection control tactics are included in each plan. These tactics include phase skipping, transfer of spare time, gapping and defining phases which will benefit from spare time or additional time gained by cycle time increase.

Each subsystem has five offset plans. These internal offsets are predetermined as part of the input database. Internal offsets can vary according to the current cycle time and an input parameter, known as the progressive speed factor, governs the percentage change in offset.

The determination of each of the three timing elements is therefore independent of the others, although all three are affected by the degree of saturation.

Cycle length is continuously variable, cycle by cycle, while splits and offsets vary in steps (by plan change) and continuously (by modification of the plan on the basis of cycle length and system activity level).

In the light traffic conditions, it is usual for SCATS to minimize stops, in medium traffic to tend more to minimize overall delay, while in congested conditions, splits and offset tend towards maximizing throughput on the major routes.

### 2.2.3 OPAC (Optimized Policies for Adaptive Control)

The strategy was originally developed at the University of Lowell. The OPAC strategy is the culmination of a research effort that included the development of three optimization algorithms. The first algorithm, OPAC-1, was designed as a basis for future OPAC strategy development. OPAC-1 incorporates dynamic programming techniques in the solution of the traffic control problem.

The second optimization algorithm, OPAC-2, is a simplification of the OPAC-1 algorithm. It was designed as a building block in the development of distributed on-line strategy. In order to use only available flow data without degrading the performance of the optimization procedure, a "rolling horizon" concept was applied to the OPAC-2 algorithm. This version is named ROPAC. OPAC-RT is a traffic signal control system that implements the ROPAC strategy in real time. The system uses traffic data collected from detectors located well upstream (400 to 600 feet) of the stop-line on all approaches to an intersection. Signal timings are dynamically optimized in a demand-responsive manner using a rolling horizon scheme.

## 3. METHODOLOGY FORMULATION

This chapter presents a summary of the traffic control policy developed in the previous paper. The reader encouraged to refer the previous paper or author' s dissertation (6) for further detail. The formulations presented describe the relatioships among the desired signal parameters (phase duration, cycle length and offset); the known approach geometrics (approach length and number of lane); the known arterial and cross street traffic volumes and turn movements; and estimates of traffic operations (speed, queue behavior).

Followings are the final formulation of IMPOST developed in the previous paper.

Objective Functions :

$$Max \sum_{i=1}^{n-1} \omega_i^{mi} \Delta_i + \overline{\omega_i}^{\overline{mi}} \overline{\Delta_i}$$

Constraints :

Phase Offset at an Intersection

$$\delta_i \leq \overline{r}_i - [g_{c,i}]_{min} \qquad i=1, n$$

$$\delta_i \geq [g_{c,i}]_{min} - r_i$$

Phase Optimization at an Intersection

$$\delta - L + M \cdot y1 \geq 0$$

$$-\delta - \overline{L} + M \cdot y2 \geq 0$$

$$\delta - L + \overline{L} + M \cdot y3 \geq 0$$

$$-\delta + L - \overline{L} + M \cdot y3 \geq 0$$

$$\delta - \overline{r} + r + M \cdot y4 \geq 0$$

$$-\delta + \overline{r} - r + M \cdot y4 \geq 0$$

$y1 + y2 + y3 + y4 = 3$ *(yi : binary variable)*

Queue Length

$$r_{o,i} \geq K_{11,i} \qquad i=1, n-1$$

$$r_{o,i} \leq K_{7,i} \qquad i=1, n-1$$

Signal Offset between Intersections

$$\Delta_i \geq K_{0,i} - K_{1,i}\, r_{0,i}$$

Case A & B Metered, and Unmetered  i=1, n-1

$$\Delta_i \leq 1 \qquad \text{Case B}$$

$$\Delta_i \leq K_{2,i} - K_{3,i}\, r_{0,i}$$

Case A, Metered$(r_o + (\Delta r)_B \leq 1 - \frac{W}{L})$  i=1, n-1

$$\Delta_i \leq K_{4,i} - K_{5,i}\, r_{0,i}$$

Case A, Metered$(r_o + (\Delta r)_B > 1 - \frac{W}{L})$  i=1, n-1

$$\Delta_i \leq K_{6,i} - K_{1,i}\, r_{0,i} \qquad \text{Unmetered} \quad i=1, n-1$$

$$\Delta_i + \delta_{i+1} + \Delta_i - \delta_i = l_i \; ; \qquad i=1, n-1$$

Conditions :

$$g_i = \frac{(G_B)_i}{C_a} ; \qquad i=1, n$$

$$\overline{g_i} = \frac{(\overline{G_B})_i}{C_a} ; \qquad i=1, n$$

$$r_i = 1 - g_i ; \qquad i=1, n$$

$$\overline{r_i} = 1 - \overline{g_i} ; \qquad i=1, n$$

$$X_{c,i} = \left[\frac{V_C Ch}{(3600(C - max[G_B, \overline{G_B}] - (AR)_B - s))}\right]_i ; \; i=1, n$$

$$[g_{c,i}]_{min} = \min[r_i, \overline{r_i}] \cdot \min\left[\frac{1, X_{c,i}}{(Xc)_{max}}\right] - \frac{(AR)_B}{C_a} ; \qquad i=1, n$$

For metered approaches, N*l*=0.

Approach metered if $\left[\frac{V_B C_a}{3600}(1 - P_B)(1 - P_A^L) + \frac{V_B C_a}{3600} P_C \frac{(LN)_C}{(LN)_A}\right]_l \geq \left[\frac{G - s}{h}\right]_{l+1}$

Approach unmetered if this condition is violated.

$$\omega_i = \frac{C_a}{C_i};\qquad i=1, n-1$$

$$\overline{\omega}_i = \frac{C_a}{\overline{C}_i};\qquad i=1, n-1$$

Note : Similar constraints on $\overline{r_{o,i}}$, $\overline{\Delta_i}$ using $\overline{K_{j,i}}$, for inbound approaches.

Specified Inputs

For each outbound link, i=1,n-1

$$K_{c,i} = \frac{\left[\frac{L}{v} - h + \frac{L_v}{u}\right]_i}{C_a};$$

$$K_{1,i} = \frac{\left[L\left(\frac{u+v}{uv}\right)\right]_i}{C_a};$$

$$K_{2,i} = \frac{\left[\frac{L}{v} + (L-W)\left(\frac{u-w}{uw}\right)\right]}{C_a};\ w = \frac{L_v}{h}(1-P_B)$$

$$K_{3,i} = \frac{\left[L\left(\frac{v+w}{vw}\right)\right]_i}{C_a};$$

$$K_{4,i} = \frac{\left[\frac{L}{v} + \frac{L_v}{h}(G_B - s)(1-P_B)(1-P_A^L)\left(\frac{u-w}{uw}\right)\right]_i}{C_a};$$

$$K_{5,i} = K_{1,i}$$

$$K_{6,i} = \frac{\left[\frac{L}{v} + N_c L_v\left(\frac{u-w}{uw}\right)\right]_i}{C_a};$$

$$K_{7,i} = [r_{o,i}]_{max}$$

$$K_{8,i} = \frac{C_a}{L_i}\left[\frac{uw}{u-w}\right]_i;\ K_{9,i} = \left[\frac{u(v+w)}{v(u-w)}\right]_i;\ K_{10,i} = \left[\frac{uw}{v(u-w)}\right]_i$$

$$K_{11,i} = [r_{o,i}]_{min}$$

A metered link is identified as Case B if its length satisfies :

$$L_i \geq \frac{v[2W + w(G_B - s)]}{(v+w)} + \frac{7}{5}\frac{L_v}{h}(G_A - s)$$

## 4. REAL-TIME APPLICATION OF IMPOST

The IMPOST formulation is particularly well-suited for real-time implementation. The major surveillance requirement for the real-time application of IMPOST is a reliable estimate of the actual queue length, r, on each approach at the beginning of the green phase.

Queue length can be inferred loop detector data and the known state of the signal indication. The best location for the deployment of the surveillance device can be determined beforehand. Specifically, the queue lengths that must be estimated accurately, are $[r_o]_{min}$ and $[r_o]_{max}$, as discussed later.

Green time need only be changed by adjusting end of Green interval (maintaining start of arterial green and offset) when the queue state threatens to either produce starvation (too short) or intersection spillback (too long). Thus, the queue state can be permitted to vary between established bounds. Within this acceptable range of queue length, the high priority IMP objectives I and II are both satisfied *with no change in green time required.*

Stated another way, the oversaturated traffic environment is, to some extent, "forgiving", in that changes in queue length may take place over a significant range, and yet not compromise the performance of traffic flow. Therefore, the real-time policy may not require frequent and radical changes in control timing. Given this premise, it is necessary to define the condition, for each approach, which will satisfy the primary IMPOST objectives without requiring control adjustments.

To maintain an optimal, stable control, the current queue length, r, must satisfy the condition, $[r_0]_{min} < r < [r_0]_{max}$. The current value of r and the current change of queue length, $\Delta r$, over the past cycle, may be used to change control only under conditions where an encroachment of a bound on queue length is a near-term expectation.

## 4.1 Determine Minimum Queue Length, $[r_0]_{min}$, at Beginning of Green for the Subject Link

<u>"Short" (Case A) Approaches</u>

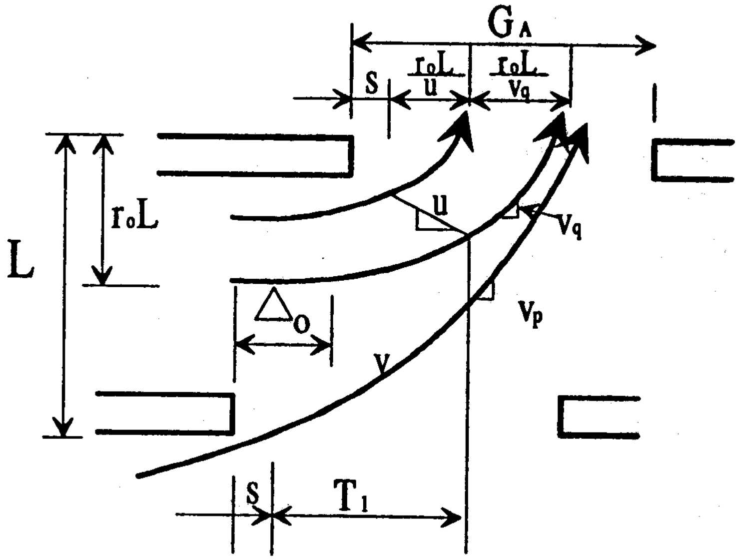


Figure 1. Minimum Queue Length to Prevent Starvation

To prevent starvation for "short" (Case A) links :

$$s + T \leq \Delta_0 + s + \frac{r_0 L}{u} + \frac{r_0 L}{v_q} \text{ where } T_l = \frac{L}{v_p}$$

Since $s_f = \frac{V_f^2}{2A}$, $s_q = (1 - r_0)L$;

if $s_q < s_f$, $v = \sqrt{\frac{A s_q}{2}}$ if $s_q > s_f$, $v = v_f \frac{s_q}{(s_f + s_q)}$

For $v_p$, set $r_0 = 0$ and $v_q$, use $r_0$

$$\text{Thus, } \frac{L}{v_p} \leq \Delta_0 + \frac{r_0 L}{u} + \frac{r_0 L}{v_q} \text{ or}$$

$$[r_0]_{min} \geq \frac{u v_q}{(u + v_q)} \left[ \frac{1}{v_q} - \frac{\Delta_0}{L} \right] \quad (1)$$

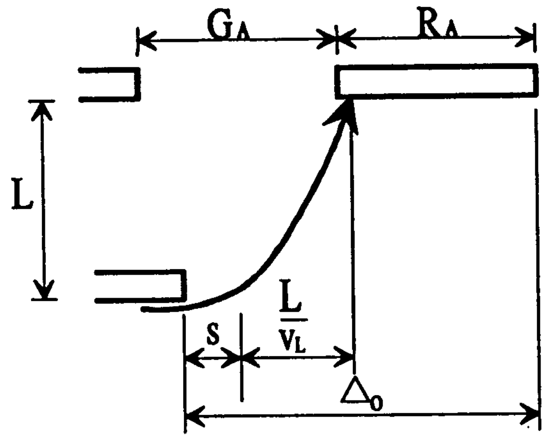


Figure 2. Test for Platoon Arriving during Red

If $\Delta_o < 0$, set $\Delta_o = \Delta_o + C$ and test for platoon arriving during red, where $v_p$ is based on $r_o = 0$. If so, $[r_o]min = 0$.

In other words, if $s + \frac{L}{v_p} \le \Delta_o \le s + \frac{L}{v_p} + R_A$, set $[r_o]_{min} = 0$ since arriving platoon should fill window with no starvation.

ELSE compute $[r_o]_{min}$ using (1)

Check if $[r_o]_{min}$ fills window

If $[r_o]_{min} > \frac{(G_A - s)}{h}\frac{L_v}{L}$, set $[r_o]_{min} = \frac{(G_A - s)}{h}\frac{L_v}{L}$

If $[r_o]_{min} < 0$, set $[r_o]_{min} = 0$.

Note : Since v depends on $r_o$, we must iterate with $v$.

Ex.: $G_A = 40$, $C = 80$, $L = 400$, $u = 20$, $v_f = 60$, $A = 4$, $s = 2$, $L_v = 20$

Assume $r_o = 0.25$ ; Calc. $s_q = 0.75 \times 400 = 300$ ;

$s_f = \frac{60^2}{8} = 450$ ; $v_p = \sqrt{\frac{4x400}{2}} = 28.3$

$$v_q = \sqrt{\frac{4x(1-0.25)x400}{2}} = 24.5$$

1) Set $\Delta_o = -20$ ; Check : Set

$\Delta_o = -20 + 80 = 60$; $\Delta_o \ge 2 + 400/28.3 = 16.1$ (Yes)

$\Delta_o \le 16.1 + 40 = 56.1$ (No)

$\therefore$ use equ. (1) with $\Delta_o = -20$

$$[r_o]_{min} = \frac{20x24.5}{20+24.5}\left[\frac{1}{28.3} + \frac{20}{400}\right] = 0.94$$

$$\frac{(G_A - s)}{h}\frac{L_v}{L} = \frac{38}{2.0}x\frac{20}{400} = 0.95 > 0.94 \quad \therefore [r_o]_{min} = 0.94$$

Iterate on v with $r_o = 0.94$ : $v_q = \sqrt{\frac{4x0.06x400}{2}} = 6.9$

$$[r_o]_{min} = \frac{20x6.9}{20+6.9}\left[\frac{1}{28.3} + \frac{20}{400}\right] = 0.44 \qquad [r_o]_{min} = 0.44$$

2) Set $\Delta_o = 0$ ; $[r_o]_{min} = \frac{20x24.5}{20+24.5}\left[\frac{1}{28.3} + 0\right] = 0.39$

Iterate : $v_q = \sqrt{\dfrac{4x0.61x400}{2}} = 22.0$

$$[r_o]_{min} = \frac{20x22}{20+22}\left[\frac{1}{28.3}\right] = 0.37$$

(Note : $\Delta_o \ngeq 16.1$ ∴ use equ. (1))

3) Set $\Delta_o$=20 ; $\Delta_o \geq 16.1$(Yes) ; $\Delta_o \leq 56.1$(Yes)

∴ Set $[r_o]_{min}$=0

"Long" (Case B) Approaches

To determine whether subject link is short (Case A), its length, L, must satisfy...

$$L < \frac{L_v}{h}[G_A - s + (1 - P_B)(G_B - s)] + (W+B)$$

where

W = Width of upstream intersection

B = Safety buffer of tail of block to protect against spillback

If the subject link length, L, exceeds this value, this approach belongs to Case B. For Case B approaches, the minimum queue length must satisfy the following :

1. Completely supply the green window downstream.
2. In addition, fill half of the available storage after accommodating the queue of step 1 plus the total inflow from the feeder link.

All Case B approaches must have a length, L, that satisfies...

$$L \geq \frac{L_v}{h}[G_A - s + (1 - P_B)(G_B - s)] + (W+B)$$

For these links, $[r_o]$min is computed independent of $\Delta_o$ :

$$[r_o]_{min} = 0.5 - \frac{(W+B)}{2L} + \frac{Lv}{2hL}[G_A - s - (G_B - s)(1 - P_B)]$$

s.t. $[r_o]_{min} \geq \dfrac{Lv}{hL}(G_A - s)$

Ex. : L=1000; W=60; Lv=20; h=2; B=40;GA=GB=40; s=2; pB=0.1

Check:L $\overset{?}{<} \dfrac{20}{2}$[38+0.9x38]+100=822 No. Link is Case B

$$[r_o]_{min} = 0.5 - \frac{100}{2000} + \frac{20}{2x2x1000}(38 - 0.9(38)) = 0.47$$

Check : $[r_o]_{min} \overset{?}{\geq} \dfrac{20}{2x1000}$ x38 = 0.38 OK

## 4.2 Determine Maximum Queue Length at Beginning of Green for the Subject Link

IF $T_u > G_B$ THEN

*Calc.* $[r_o]_{max}$ *such that* $T_w = G_B$

ELSE

*Calc.* $[r_o]_{max}$ *such that* $\dfrac{G_B - T_u}{h} = M$ *and* $\dfrac{(T_u - T_w)}{h} = M$

ENDIF

Where M=No. of vehicles who enter intersection but are blocked by effective red which is of duration ($T_u$ -$T_w$). That is, M vehicles enter intersection during ($T_u$ -$T_w$) and then enter receiving link during ($G_B$ -$T_u$) : implies $T_u$ -$T_w$

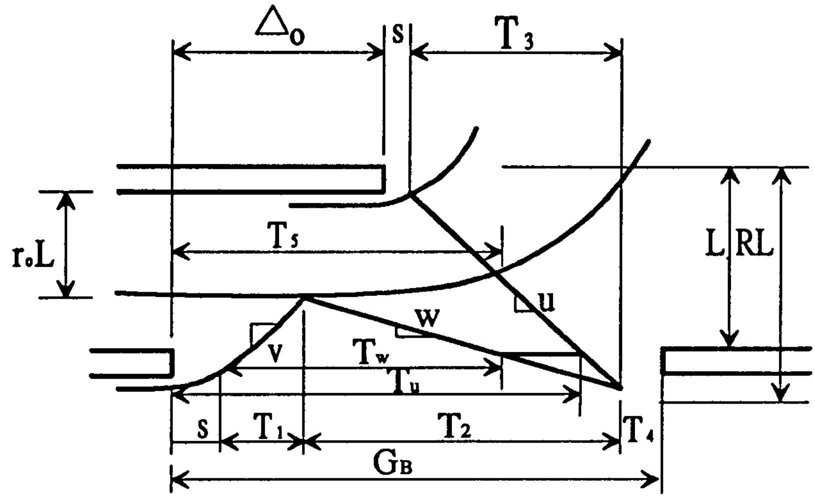


Figure 3. Maximum Queue Length to Prevent Spillback

$=G_B - T_u$, so long as $M \leq M_s$ where $M_s$ = maximum number of vehicles that can be stored within intersection=$W/L_v$.

Note : When the discharge move hits the red phase at intersection B ($T_u > G_B$), then we want $T_w = G_B$ to avoid spillback. When $T_u < G_B$, we can allow spillback providing all blocked vehicles can discharge by the end of green.

$$T_l = \frac{(1-r_0)L}{v};\ T_2 = \frac{L[R-r_0]}{w}$$

$$T_3 = \frac{RL}{u}\ ;\ w = \frac{L_v}{h}(1-P_B)$$

From above sketch : $\Delta_0 + s + T_3 = s + T_1 + T_2$

Substitute : $\Delta_0 + \frac{RL}{u} = \frac{L(1-r_0)}{v} + \frac{L(R-r_0)}{w}$

Solving for $r_0 = \left(\frac{wv}{w+v}\right)\left(R\left(\frac{u-w}{uw}\right) + \frac{1}{v} - \frac{\Delta_0}{L}\right)$

With $R=1$, $T_u = \Delta_0 + s + \frac{L}{u}$

$$T_w = s + T_l + \frac{L(1-r_0)}{w} = s + L(1-r_0)\left(\frac{1}{v} + \frac{1}{w}\right)$$

$$= s + L(1-r_0)\left(\frac{w+v}{wv}\right)$$

To assure no spillback, R=1 and $T_w = T_u$

Setting

$s + L(1-r_0)\left(\frac{w+v}{wv}\right) = \Delta_0 + s + \frac{L}{u}$ yields.

$$[r_0]^{(1)}_{max} = 1 - \frac{wv}{(w+v)}\left[\frac{1}{u} + \frac{\Delta_0}{L}\right]$$

If $T_u > G_B$, set $T_w = G_B$ $\quad s + L(1-r_0)\frac{w+v}{wv} = G_B$ *yields* :

$$[r_0]^{(2)}_{max} = 1 - \frac{wv}{(w+v)L}(G_B - s)$$

If $T_u \leq G_B$, calc. $M = \min\left[\frac{G_B - T_u}{h}, \frac{w}{L_v}\right]$ alc.

$[r_0]^{(3)}_{max}$ such that $\frac{T_u - T_w}{h} = M$

With $T_w = T_u - Mh$ ; $s + L(1 - r_0)\frac{(w+v)}{wv} = T_u - Mh$ yields

$$[r_0]^{(3)}_{max} = 1 - \frac{wv}{L(w+v)}\left[\Delta_0 + \frac{L}{u} - Mh\right]$$

Note : Lead vehicle of entering platoon interacts with the last vehicle in the standing queue when $T_5 > s + T_1$(Figure 3). This condition (i.e., interaction) occurs when

$\Delta_0 > \frac{L}{v}\left[1 - \frac{r_0(u+v)}{u}\right]$. If satisfied, calcula $[r_0]^{(2)}_{max}$, or $[r_0]^{(3)}_{max}$ as appropriate. If not, calculate $[r_0]^{(4)}_{max}$

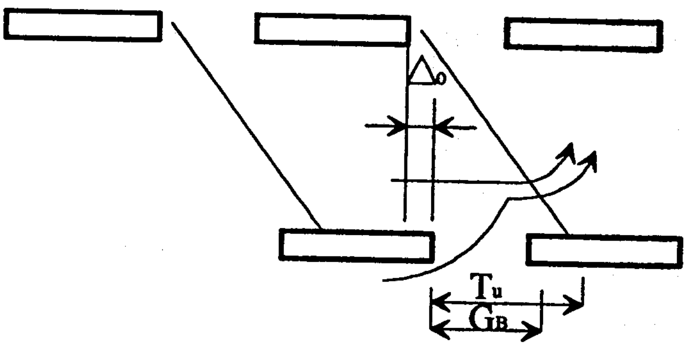


Figure 4. Test for Platoon Interaction with Last Queue

IF $\Delta_0 \geq \frac{L}{v}\left[1 - \frac{r_0(u+v)}{u}\right]$

when $r_0$ measured as $r_{BG}$(beginning of green for feeder link, THEN Calculate $[r_0]^{(2)}_{max}$ or $[r_0]^{(3)}_{max}$

ELSE $\left(\Delta_0 < \frac{L}{v}\left[1 - \frac{r_0(u+v)}{u}\right], \text{where } r_0 = r_{AG}\right)$

Calculate $[r_0]^{(4)}_{max}$

$$[r_0]^{(4)}_{max} = 1 - \frac{W+B}{L} - \frac{L_v}{L}\left[N_C P_C \frac{(LN_C)}{(LN_A)} + \frac{(G_B - s)}{h}(1 - P_B) - \frac{(G_A - s)}{h}\right]$$

Ex. : w=10, $(LN)_A=2$, $N_C=16$, $p_c=0.25$, $(LN)_C=1$, B=40, $p_B=0$, W=40, L=500, $v_f=60$, u=20, h=2, $G_A=G_B=40$, s=2, A=4, $L_v=20$

Assume. $v_0 = 0.6$ Calc. $s_q = 0.4x500 = 200$, $s_f = 450$,

$$v = \sqrt{\frac{4x200}{2}} = 20$$

1) Set $\Delta_0 = -20$.

$$T_u = -20 + 2 + \frac{500}{20} = 7 < G_B = 40 ; M = \min\left[\frac{40-7}{2}, \frac{40}{20}\right] = 2$$

$$[r_0]^{(3)}_{max} = 1 - \frac{10x20}{500x30}\left[-20 + \frac{500}{20} - 2x2\right] = 0.99 \quad [r_0]_{max} \cong 1$$

Iteration on v does not change result. Now check on interaction

$$\Delta_o \overset{?}{\gtrless} \frac{L}{v}\left[1 - r_o\frac{(u+v)}{u}\right].$$ Est. v=6, $r_o$=1, RHS= -25

∴ There is interaction :

$\Delta$ >-25. *Use of* $[r_o]^{(3)}_{max}$ is justified.

2) Set $\Delta$o=0.

$$T_u = -20 + 2 + \frac{500}{20} = 27 < G_B = 40;\ M = \min\left[\frac{40-21}{2}, \frac{40}{20}\right] = 2$$

$$[r_o]^{(3)}_{max} = 1 - \frac{10x20}{500x30}\left[0 + \frac{500}{20} - 2x2\right] = 0.72$$

Iterate on v :

Assume $r_o$=0.75, $v$=15.8,

$$[r_o]^{(3)}_{max} = 1 - \frac{10x15.8}{500x25.8}\ [0.25+25-4] = 0.74$$

Check for interaction :

$$\Delta_o \gtrless \frac{L}{v}\left[1 - r_o\frac{(u+v)}{u}\right] = -10.3$$

there is interaction : 0>-10.3. Use of $[r_o]^{(3)}_{max}$ is justified.

3) Set $\Delta_o$=20. Check $T_u > G_B$ ; 47>40.

Estimate v=20, $r_o$=0.5.

Test

$$\Delta_o \gtrless \frac{L}{v}\left[1 - \frac{r_o(u+v)}{u}\right] = 0$$ there is interaction (20>0)

$$\therefore \text{Use } [r_o]^{(2)}_{max} : [r_o]^{(2)}_{max} = 1 - \frac{10x20}{30x500}x38 = 049$$

(*based on* $\Delta_o$=20)

4) Set $\Delta_o$ = -30

$$Tu = -30 + 2 + \frac{500}{20} = -3 : Calc.\ [r_o]^{(3)}_{max}(M=2)$$

$$[r_o]^{(3)}_{max} = 1 - \frac{10x20}{500x30}\left[-30 + \frac{500}{80} - 2x2\right] = 1.12;\ use 1$$

Check for interaction :

$$\Delta_o \overset{?}{\gtrless} \frac{500}{5}\left[1 - \frac{1(25)}{20}\right] = -25.$$ *But* $\Delta_o$=-30<-25 *N.G*

No interaction. Use

$$[r_o]^{(4)}_{max} = 1 - \frac{80}{500} - \frac{20}{500}\left[16x.25x\frac{1}{2} + \frac{38}{2}x1 - \frac{38}{2}\right] = 0.76$$

## 4.3 Adjustment of Green Time Each Cycle

The need to adjust green time remains a primary consideration if the queue length, r, moves outside the acceptable range. A question arises: How will such an adjustment at one or more intersections affect the validity of the system-wide signal timing policy computed by IMPOST?

Examination of the IMPOST constraints formulation reveals that only one constraint parameter, $K_{4,i}$, explicitly references the green phase duration, $G_B$. Furthermore, this constraint applies only to the Case B situation (i.e., long approaches) when the entire platoon can be compressed without incurring spillback. As discussed earlier, a "reasonable" but non-optional offset on a long approach would usually have little effect on productivity.

It therefore appears that the IMPOST solution which yields signal offsets, is relatively insensitive to small, corrective changes in green phase durations to maintain queue stability. That is, the vector of offsets computed by IMPOST will remain "near-optimal" the point of view of satisfying the IMPOST objectives, even in the presence of occasional variations in green time about the computed values, when conditions dictate.

Of course, it is necessary to update the IMPOST solution when "important" changes in the traffic environment take place :

- Over time, undersaturated approaches may become saturated, and vice-versa, due to changes in demand.

- Incidents may occur on the freeway and/or on the arterial, markedly influencing the arterial demand or demand on the off-ramps connected to the arterial.

- Travel patterns (i.e., turning movements, $P_B$ and $P_C$) may change appreciably.

- Equity considerations may dictate changes in policy.

For any of these changes, it will be advisable to compute new IMPOST solutions which will yield a new base policy. The parameters (green phase durations) of this new policy can then be adjusted, as needed, and as frequently as required, until the next IMPOST update becomes necessary.

Followings are the procedures how to adjust green time of subject node:

1. Solve MILP for average traffic conditions
2. Set optimal signal solutions of step 1
3. Compare optimal and actual queues
4. Change green time to control queue differences every cycle
5. Check link state

If link state is changed, go to step 1

If link state is unchanged, go to step 3

The green time adjustment between two nodes is as follows :

Direction, k*

⑤→④→③→②→①

The average change in queue length per-lane is computed as follows:

Change in Vehicle Content = Total inflow - Total outflow

$$(LN)_k^a \frac{\Delta(r_0 L)}{L_v} = (LN)_B^{(a)} S_B^{(a)}(G\text{-}s)_B + (LN)_B^{(c)} S_B^{(c)}(C\text{-}G_B\text{-}G_B^L\text{-}s) - (LN)_A^{(a)} S_A^{(a)}(G\text{-}s)_A$$

where

$G_B^L$ = Sum of lead+lag L.T. phases

$\Delta(r_0 L)$ = Change in queue length over one cycle, feet

$L_v$ = Average vehicle length, ft/veh

$S^{(j)}$ = Average vehicle discharge rate, veh/sec, for through (j=a) and turning traffic (j=c)

$G_{A,B}$ = Green time, sec, at (downstream, upstream) nodes

s = Start-up lost time, sec.

$G^{(a)}$ = Green time servicing arterial approach

$G^{(c)}$ = Green time servicing cross street approach(es)

$(LN)_X^{(j)}$ = Number of lanes on approaches (j=a: arterial, j=c: cross street)

$$S_B^{(a)} = (1 - p_B)\, S^{(a)}$$

$$S_B^{(a)} = X_C\, p_C\, S^{(c)}\ ;\ S_A^{(a)} = S^{(a)}$$

where

$p_B$ = Percent of turners on arterial feeder

$p_C$ = Percent of turners on cross street feeder(s) (avg.)

$X_C$ = Percent saturation on cross street

Solving for $G_B$:

$$G_B = s + \frac{\frac{(LN)_A^{(a)}\Delta(r_oL)}{Lv} - (LN)_B^{(c)}S_B^{(c)}(C - G_B^L) + (LN)_A^{(a)}S_A^{(a)}(G-s)_A}{(LN)_B^{(a)}S_B^{(a)} - (LN)_B^{(c)}S_B^{(c)}}$$

Let $R^{(a)} = \frac{(LN)_A^{(a)}}{(LN)_B^{(a)}}$, $R^{(C)} = \frac{(LN)_B^{(c)}}{(LN)_B^{(a)}}$,

$G_B^L$ = Green time for left-turn phase

$$G_B = s + \frac{\frac{R^{(a)}\Delta(r_oL)}{Lv} - R^{(c)}S_B^{(c)}(C - G_B^L) + R^{(a)}S_A^{(a)}(G-s)_A}{S_B^{(a)} - R^{(c)}S_B^{(c)}}$$

Ex.: L=400, $[r_o]$opt.=0.5, $r_o$=0.4, s=2, C=80, $G_A$=40,
s=2, $X_C$=0.6, $p_C$=0.3, $G_B^L$=0, $p_B$=0.1, $R^a$=1, $R^C$=0.5,
$L_v$=20, $S^C$=0.42, $S_A^a$=0.53,
$S_B^C$=0.42x0.6x0.3=0.076, $s_B^a$ = 0.9x0.53

$$G_B = 2 + \frac{\left\{1x(0.5-0.4)\frac{400}{20} - 0.5x0.076x80 + 1x0.53x38\right\}}{((0.9)(0.53) - 0.5x0.076)} = 45.5$$

Another option is to sweep downstream (as discussed below) to adjust the green times at the downstream nodes of each link. Here, we must solve for $G_A$:

$$G_A = s + \frac{-R^{(a)}\Delta(r_o)\frac{L}{L_v} + R^{(c)}S_B^{(c)}(C - G_B{}^L) + (S_B{}^{(a)} - R^{(c)}S_B{}^{(c)}(G-s)_B)}{R^{(a)}S_A{}^{(a)}}$$

Ex. : Same as previous Ex. except $G_B$=40

$$G_A = 2 + \frac{-1x(0.5-0.4)x\frac{400}{20} + 0.5x0.076(80-0) + (0.9x.53-0.5+0.076)(38)}{1x0.53}$$

=35.4

If $G_B^L$ is the lag phase, then any change in $G_B$, in either direction, will influence the duration of $G_B^L$. We must set a lower bound on $G_B^L$ which will limit how much $G_B$ can be changed.

We must have an estimate of left-turn percentage, which led to the determination of L, the minimum duration of the left-turn phase. For the approach where left-turners are serviced by the lag phase, a growing left-turn queue can only be addressed by increasing the [downstream] green -- any increase in this green time will automatically increase the length of the left-turn phase. This is an exception to the protocol of changing the upstream green to control queue lengths.

Establish the following rules for the upstream intersection whose arterial approach link has a left-turn movement serviced by a lag phase:

1. Allow the left-turn phase duration (if L>1 sec) to be reduced to L/2 if the left-turn queue on the feeder approach is not "excessive".
2. If it excessive on the feeder approach, do not permit the green time for that link to be reduced. Instead, increase the green time at the downstream intersection to adjust the queue on the subject link and sweep downstream to adjust the green times to reflect this departure the "upstream-sweep" protocol.
3. After the sweep downstream, return to the upstream protocol, starting with the original feeder link.

## 5. EXPERIMENTATION RESULTS

### 5.1 Enhancements of WATSim

WATSim, developed by KLD Associates, Inc. further expanded TRAF-NETSIM to perform a microscopic, stochastic simulation of traffic operations on highway networks comprised of freeways, ramps and surface streets. We used the WATSim simulation model to evaluate IMPOST,TRANSYT and PASSER strategies for oversaturated traffic conditions.

The fact is that the existing WATSim does not have an algorithm of controlling queues, which is an essential algorithm to apply IMPOST. Therefore, it is essential to enhance the tool which is available, namely WATSim, so that it can control queues.

The logic flow for WATSim program subroutines added is described briefly in Figure 5. For the purpose of controlling queues, the following subroutines were added.

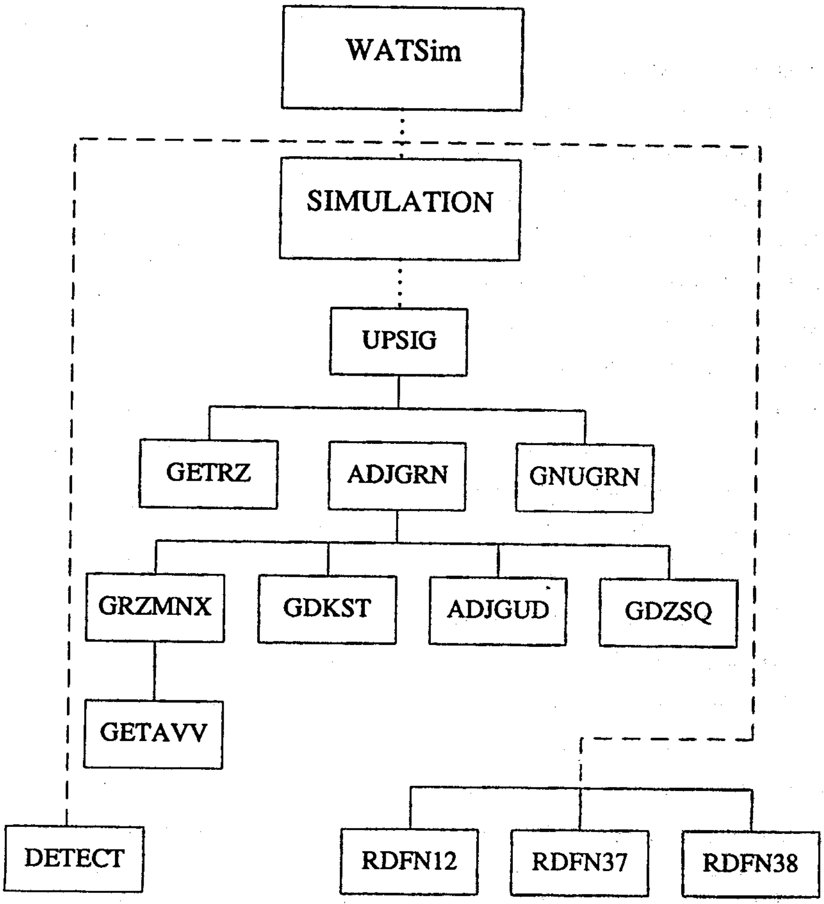


Figure 5. Added Subroutine Flow of WATSim

ADJGRN : Get Min queue and Max queue and arterial direction to be analyzed. Then perform a gradient search to determine the green time at the C.I. that will maximize the green time adjustments, if such adjustments are needed. This routine is called once per cycle.

ADJGUD : Identify downstream link of arterial. Calculate the value of green time at upstream node that will have the difference between the current and optimal queue lengths, if possible. Then get feeder link and repeat. Continue sweeping upstream until first link is processed.

DETECT : This routine computes the contribution of this vehicle to the occupancy of the detector(s) it crosses or dwells on, during the prior time-step. If it crosses the detector, then the detector count is incremented. Note that the detector must be at least 90 feet upstream of the stop bar for this logic to work. That is, the vehicle must now be on the same link as the detector it crossed.

GDKST : Calculate D(K) = SUM (DELTA RO) ** 2 for all saturated arterial links in both directions. Green times in worse direction, K, (identified by higher value of D(K)), will be adjusted elsewhere, if needed. DELTA RO is difference between optimal and estimated queue lengths. The estimated queue lengths are computed when clock is at beginning of green(start of interval one), and are stored in QCURR array.

GDZSQ : Sweep down arterial calculating and summing (DELTA GREEN = NEW GREEN - OLD GREEN) ** 2. The DELG array was primed in ADJGUD.

GETAVV : Get the average speed of lead vehicle in incoming platoon.

GETRZ : This routine averages the queue lengths on the arterial approach links, IL, to the specified node, I1, at the start of green and stores the values of RO. UPSIG calls this routine at beginning of interval number 1, at node, I1.

GNUGRN : Retrieve new green times and movements serviced temporary arrays. This routine is entered at beginning of each cycle at this node.

GRZMNX : Calculate Min. queue and Max. queue for every arterial link, IL, belonging to arterial, IA. Select proper equation based on when queue discharge wave arrives at upstream intersection (for Max. RO) and on whether link is short/long (for Min. RO).

RDFN12 : This software loops to read Type 12 Records and stores the data into the link array.

RDFN37 : This software loops to read Type 37 Records and stores the data into the link array.

RDFN38 : This software loops to read Type 38 Records and stores the data into the link array.

UPSIG : Update the signal timings.

## 5.2 Simulation Runs and Results

The fundamental issue of this section is to evaluate the MOEs between IMPOST, PASSER II and TRANSYT 7F strategies for oversaturated arterials. To assess system performance on the basis of traditional traffic network performance measures, optimal signal settings derived in IMPOST, PASSER II and TRANSYT 7F were entered into the WATSim model. Table 1 was used as input parameters for the simulations. Scenario 1 and 2 represent oversaturated and undersaturated conditions, respectively.

Table 1. Input Parameters for The Simulation

| | Scenario 1 | Scenario 2 |
|---|---|---|
| # of Lane of Arterial | 2 with LT bays | 2 with LT bays |
| # of Lane of cross street | 1 | 1 |
| Cycle Length | 100 sec. | 70 sec. |
| Min g/c cross street | 0.28 | 0.29 |
| g/c at C.I. | 0.5 | 0.5 |
| Traffic Volume | See Figure 6 | See Figure 7 |

The statistical results of simulation are tabulated in Table 2.

Table 2. Comparison Results between Three Strategies

| | Scenario 1 | | | Scenario 2 | |
|---|---|---|---|---|---|
| | IMPOST | PASSER II | TRANSYT 7F | IMPOST | PASSER II |
| Total Volume (Veh.) | 5438 | 4981 | 5168 | 3184 | 3196 |
| Total Travel Time (Hour) | 267 | 364 | 340 | 74.7 | 72.8 |
| Travel Time per Vehicle (Min.) | 3 | 4.4 | 4 | 1.4 | 1.38 |

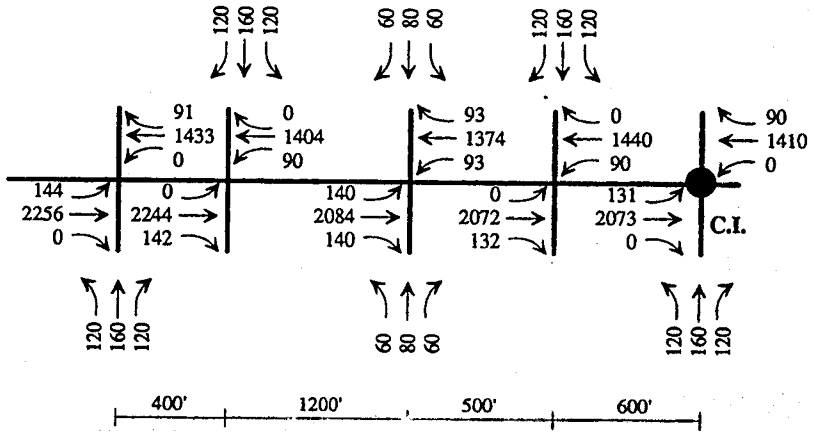


Figure 6. Traffic Movements and Signal Spacing for Scenario 1

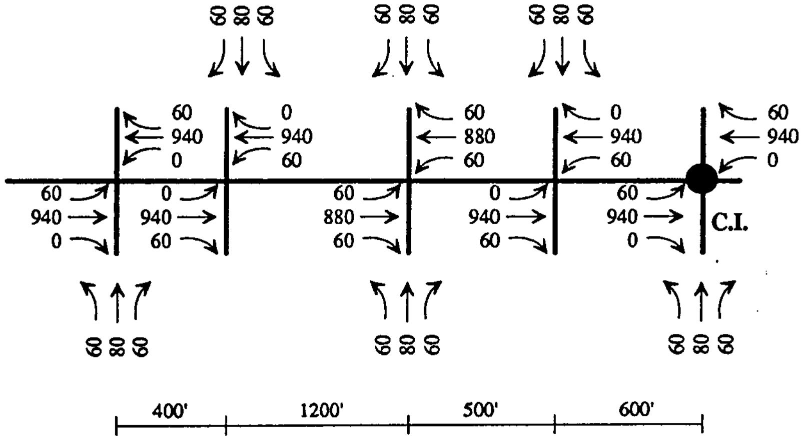


Figure 7. Traffic Movements and Signal Spacing for Scenario 2

As shown in Table 2, even though IMPOST discharges more vehicles under oversaturated conditions, total travel time taken is less than that of PASSER II and TRANSYT 7F during one-hour simulations. In order words, travel time per vehicle serviced by IMPOST, PASSER II and TRANSYT 7F signal settings are three minutes, 4.4 minutes, and four minutes, respectively. The signal setting of IMPOST take 30 percent and 20 percent less travel time per vehicle than that of PASSER II and TRANSYT 7F, respectively. These results were expected. Because PASSER II and TRANSYT 7F does not meter, queues are growing over from the critical intersection and spillback is spread over. However, since IMPOST does meter, queues are not growing and they do not experience spillback. Therefore, metering is essential under oversaturated conditions. Interestingly, the IMPOST solution for undersaturated conditions is almost as good as that of PASSER II.

## 6. CONCLUSIONS

The results presented describe the relationships among the signal parameters (phase duration, phase sequence, cycle length and offset); the approach geometrics (approach length and number of lanes); the arterial and cross street traffic volumes and turn movements; traffic operations (speed, queue formation) and the response of the traffic environment (extent of starvation and spillback, and loss of productivity).

For oversaturated networks servicing two-way traffic, the IMP concepts were applied in the development of a Mixed-Integer Linear Programming (MILP) formulation named IMPOST for two-way arterials. IMPOST formulations expressly treat all signal control parameters and queue length as dependent [solution] variables.

A discussion of the potential for IMPOST as a real-time control policy was presented. It was shown that the policy was stable in the presence of fluctuations in demand within stated bounds on queue length. It was also demonstrated that the policy can adjust the control parameters on a cycle-by-cycle basis, continually responding to changes in demand and queue formation, between optimization updates.

In the assess of system performance, signal settings of IMPOST took 30 percent and 20 percent less travel time per vehivle than those of PASSER II and TRANSYT 7F, respectively, under oversaturated 5 intersection arterial.

The evaluation should proceed, stage by stage, in a progressive manner. If this policy proves to be beneficial, then followings should be extended in addition to the extensions of the previous paper. Each extension to IMPOST should be subject to simulation and field testing.

- Current objective function of IMPOST is to maximize queue lengths to maximize the productivity. Another objective function could be considered for real-time purpose to prevent actual queues going to outside range frequently

$$(i.e.: MIN \sum (r_i - \frac{[r_i]_{max} + [r_i]_{max}}{2})^2).$$

- Current IMPOST is manually interfacing with WATSim. However, automatic interfacing algorithm should be developed to be implemented to real world.

A parallel research activity should identify hardware and software systems that can accurately estimate queue lengths over time. Detector counts measure vehicles serviced, not vehicle demand when the traffic environment is oversaturated. The most reliable measure of oversaturation for a real-time system is the quantitative history of queue length growth over time.

Subject to the successful testing of the policy in a fixed-time control environment, it should then migrate to a real-time control system. The unique ability of this policy to accommodate both oversaturated and undersaturated traffic flow conditions in an [arterial] network offers considerable promise that should be explored.

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## Notation

The variable having bar(-) sign means inbound approach.

$w_i$ : $C_a$ / $C_i$

$C_a$ : System-wide cycle length

$C_i$ : Cycle length at intersection i

$m_i$ : User-specified exponents for the outbound approaches

$\Delta_i$ : Offset between the start of green phase servicing outbound traffic at intersection i, and the start of the green phase servicing outbound traffic at intersection i+1

$\delta_i$ : Offset between the start of the green phase servicing outbound traffic and the start of the overlapping green phase servicing inbound traffic at intersection i

$R_i$ : Duration of red phase servicing outbound

$r_i$ : Duration ratio of red phase servicing outbound ( Ri/Ca )

$g_i$ : Duration ratio of green phase servicing outbound ( Gi/Ca )

$[g_{c,i}]_{min}$ : Minimum green time ratio for cross street

L : Duration of protected left-turn or Link length

M : Big number

$r_{o,i}$ : Optimal queue ratio

$I_i$ : Zero or an integer

$G_B$ : Duration of green phase at up-intersection

h : headway

$X_{c,i}$ : Degree of saturation for cross street at intersection i

$V_c$ : Cross street volume per lane at up-intersection

$(AR)_B$ : Duration of all red at up-intersection

s : Start-up lost time

$N_l$ : Portion of the platoon that is stopped by the following red phase, veh/cycle

$V_B$ : Volume per lane approaching up-intersection

$P_B$ : Proportion of total traffic that leaves the arterial to turn onto the cross street(s) at up-intersection

$P_A^L$ : Proportion of left turn traffic volume at down-intersection

$(LN)_C$ : Number of lanes on the cross street approach(es) at up-intersection

$(LN)_A$ : Number of lanes on the arterial approaches

$v$, $v_p$, $v_q$ : Mean speed of lead vehicle in incoming platoon varing with different queue

$u$ : Mean speed of queue discharge wave propagating upstream

$L_v$ : Length of vehicle

W : Width of intersection

$w$ : Speed of shock wave

$N_c$ : Portion of the platoon that is compressed, veh/cycle

$V_f$ : Free flow speed

A : Mean constant acceleration