SIGNAL TIMING OPTIMIZATION BASED ON MINIMIZING VEHICLE AND PEDESTRIAN DELAY BY GENETIC ALGORITHM

BY

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THESIS

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Abstract

There are two objectives for this research. One is to develop an effective procedure to optimize intersection signal timing by minimizing total delay for both vehicles and pedestrians. The second objective is to establish guidance for pedestrian crossing phase selection (two-way or scramble) and the length of WALK phase when scramble crossing is used.

An optimization procedure for signal plans in an isolated intersection is developed. The procedure yields up to four phases for vehicles with either the two-way or scramble pedestrian crossing phase. A simple Genetic Algorithm (GA) is used in finding suitable signal plans because of the existence of a very large solution space. The GA fitness function is the total users delay (or cost).

Compared with Highway Capacity Software (HCS) GA function, the proposed procedure has the same accuracy and more capabilities. When there is no pedestrian at the intersection, with the same input, the total delay from HCS and the proposed GA procedure has no significant difference (<0.2%) before optimization. After optimization, the signal plans recommended by the proposed procedure can result in delay values that are slightly less than or at least as much as the delay values from the HCS GA optimized signal plans. However, when pedestrian delay is considered in signal timing, such a comparison could not be made because the HCS does not compute a delay for pedestrians, while the proposed GA procedure does.

Contour diagrams and look-up tables are generated to guide the decision between two-way and scramble phases. The guidance considers different combinations of vehicular volume, pedestrian volume, relative value of time, initial queue, and geometric layout of the intersection. Not only pedestrian volumes and right-turn vehicle volumes need to be taken into account, but also through (and left-turn) vehicle volumes. Scramble crossing is beneficial when pedestrian and right-turn vehicle volumes in an approach are high but through vehicle volumes are relatively lower.

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Table of Contents

Chapter 1

Introduction

There are two objectives for this research. One is to develop an effective procedure to optimize signal timing of an individual intersection by minimizing total user time (cost) which considers both vehicle and pedestrian delay. The other objective is to establish some guidance for traffic engineers to make a decision on which pedestrian crossing pattern (two-way crossing or scramble crossing) is more appropriate in a given situation. Also what appropriate scramble WALK phase length should be used, if scramble crossing is suggested.

1.1 Impact of Vehicles and Pedestrians on Signal Plans

Traffic signals generally aim at minimizing average vehicle delay, but pedestrian delay is not taken into account. Such strategy is reasonable for rural areas or highways where very few pedestrians interfere with vehicular traffic. However, in a central business district with a lot of pedestrians walking around, the strategy that only optimizes vehicle flows would not suitable because the pedestrian delay is ignored. Ignoring pedestrian delay might even result in people choosing to use vehicles more frequently than walking.

Therefore, when pedestrian flows start to have an influence on vehicle flows, pedestrian signal plans should be optimized considering delays for both groups. Traffic signal plan optimization should be a trade-off between vehicle delay and pedestrian delay by minimizing travel delay for all the travelers.

1.2 Two-Way and Scramble Pedestrian Crossing Pattern

The scramble crossing phase, which is also referred to as the “Barnes Dance” or exclusive pedestrian phase, allows pedestrians to cross the intersection in any direction, including diagonally, while all the vehicle movements are required to stop. The phase usually is activated once in each cycle. Some traffic engineers (Roess, et al., 2004) discourage the usage of the pedestrian scramble except for rural and suburban centers.

The two-way crossing phase is the most widely used pedestrian crossing phase. It is usually activated when the corresponding through traffic green signal is activated, and the two-way crossing phase sometimes can start earlier than the through green phase.

Both of the crossing patterns have advantages and disadvantages. The scramble crossing causes longer waiting time for through traffic, turning traffic, and pedestrians, but it can provide additional safety for pedestrians. Furthermore, in an intersection with high volumes of right-turn traffic and pedestrians, scramble crossing can eliminate the conflict between them and improve the capacity of the right-turn lane group (since right-turn vehicles would not block the intersection while waiting for pedestrians). Nevertheless, in an intersection with extremely heavy pedestrian flows, a major enforcement problem could be brought by the difficulty of clearing pedestrians out of the intersection at the end of the scramble phase, which causes extra waiting time for vehicles (Roess, et al., 2004). On the contrary, the two-way crossing would allow through traffic, turning traffic, and pedestrians to have less waiting time, but it might not be beneficial in a high volume intersection especially with high volumes of right-turn traffic and pedestrians.

However, very few studies have been done on the criterion to decide which pattern is more suitable in a certain situation. Partially due to the dominant position of the two-way crossing pattern and most people's preference to driving in US, the Highway Capacity Manual 2000 discusses neither the scramble crossing nor the pedestrian delay.

1.3 Thesis Organization

The thesis is organized into seven chapters. The first chapter describes the objectives of this thesis and relevant background information. The second chapter is literature review which includes previous researches on signal timing considering both pedestrians and vehicles and on the application of Genetic Algorithms to signal timing optimization. The third chapter discusses the development of the signal plan optimization mythology including modeling total user time and establishing simple GA optimization procedure. The fourth chapter verifies the proposed GA optimization procedure in 10 tests from 4 aspects – vehicle aspect, pedestrian aspect, vehicle and pedestrian integration aspect, and total user time aspect. The fifth chapter explicates the effectiveness of Genetic Algorithms from 3 aspects. The comparison analysis between the HCS GA function and the proposed GA procedure is included in this chapter. The sixth chapter demonstrates the contribution of the GA procedure from 6 aspects, including relative time value and initial queue impact analysis. Contour diagrams and tables, as the selection guide of pedestrian crossing patterns and scramble WALK phase lengths, are generated in this chapter. Pedestrian delay and vehicle delay are also compared between two-way and scramble crossing in chapter six. The last chapter summarizes the findings and possible areas for further research.

Chapter 2

Literature Review

Few studies have been done to investigate the balance between pedestrian delay and vehicle delay either at an isolated intersection or in a network.

Noland (1996) analyzed the signal timing based on travel time costs of both pedestrians and vehicles at isolated intersections with high pedestrian demand. From an economic perspective, he claimed that pedestrians should be favored when high ratio of pedestrians to automobiles by decreasing automobile green phase length and increasing pedestrian green phase or by alternative strategies such as reducing major road width and closing selected streets to vehicular traffic at certain peak hours. However, Noland didn't show difference of optimized signal timing between models considering pedestrian and vehicle delay and those considering vehicle delay.

Ishaque, et al. (2005) analyzed effect of signal cycle timing on both vehicle and pedestrian delay in a hypothesized network by a VISSIM microsimulation model. Aiming at minimizing the multimodal travel delay and travel costs, they found that optimal cycle lengths under light traffic conditions (60 to 72 seconds) were shorter than optimal cycle lengths under heavy traffic conditions (90 seconds). However, they only discussed eight fixed-time noncoordinated signal plans with single or double exclusive pedestrian phases. In addition, pedestrian compliance effect was not considered in the research.

Based on their research in 2005, Ishaque, et al. (2007) studied trade-offs between pedestrian and vehicle traffic in the same hypothetical network by a VISSIM microsimulation model. Aiming at optimizing average travel cost per person in all modes of the network, they found that shorter cycle lengths were beneficial for pedestrians, and that signal plans advantageous to vehicles might be disadvantageous to pedestrians. Based on different proportions of pedestrians to vehicle users and different pedestrian time values, suitability of three different pedestrian phase types was analyzed, so that the optimal network performance could be achieved for all road users. Compared with their previous research, pedestrian compliance effect was considered in the research, and the variety of signal plans was improved. However, the variety was still limited to a two-phase vehicle signal plans with single exclusive, or double exclusive, or staggered pedestrian crossing phase(s).

In 1998, Virkler completed four research projects about pedestrian traffic control – pedestrian travel time estimation, pedestrian signal coordination benefits, pedestrian compliance effect, and pedestrian crossing timing:

(1) By referring to test vehicle technique for travel time, Virkler developed a method for pedestrian travel time, which could be viewed as a combination of average-car and floating-car techniques. The pedestrian travel time included walking time based on average pedestrian flow rate and queuing delay in signalized or unsignalized intersections based on random arrivals. However, his method ignored signal coordination effect. Therefore, it might overestimate or underestimate signal delay experienced by platoon pedestrians.

(2) Virkler studied signal coordination benefits for pedestrians through field data from 10 intersection approaches. He found that ideal offsets with a given cycle length tended to be shorter for longer green time.

(3) According to Virkler's research, 69 percent of pedestrians arriving at the curb during the flashing Don't Walk phase would enter the crosswalk. Thus, compared with complete

signal compliance, delay would reduce 22 percent based on random arrivals.

(4) Virkler analyzed various methods developed to determine appropriate pedestrian crossing timing at signalized intersections. Based on field data, relationships to describe pedestrian flow at signalized crossings were developed, and certain improvements of signal timing parameters were recommended under high-volume conditions and with two-way flow within a crosswalk.

A deterministic model (Bhattacharya, 2004; Bhattacharya and Virkler, 2005) was proposed that incorporated both pedestrian and vehicle delay in a signal coordination plan. The author(s) analyzed the running results of the model on a hypothesized five-intersection arterial with various offsets and found that the best offsets for vehicles and pedestrians along the arterial were not necessarily the same. In order to minimize total pedestrian and vehicle user cost, an optimal signal coordination plan could be achieved by balancing between pedestrian and vehicular delay.

Li, et al. (2009) developed a traffic signal optimization strategy, programmed in Matlab, for an individual intersection to minimize weighted total vehicle and pedestrian delay. The total vehicle and pedestrian delay on sidewalk were calculated based on their deterministic queuing model respectively. Total pedestrian delay on crosswalk was calculated based on an empirical pedestrian speed model, which considered interactions between pedestrian platoons. According to a case study at a Japanese Intersection, the proposed model improved average person delay by 10% without changing existing cycle lengths, and the further improvement could reach 44% with additional cycle length optimization.

As discussed in Artificial Intelligence in Transportation (TRB, 2007), since the Genetic Algorithm (GA) was developed maturely in '90 s, it has been employed to solve lots of complex transportation problems. Among all of them, traffic signal optimization is one of most popular areas where GA has been applied.

Foy, et al. (1992) used GAs to optimize cycle lengths, green splits, and phase sequences in a four-intersection network by minimizing the total average wait time per car. Green splits were expressed by the percentage of cycle lengths, while phase sequences determined whether north-south or east-west direction green signal displayed first at each intersection, but neither turning movements nor turning phases were considered in their research. According to test runs, the traffic GA always converged to reasonable timing strategies.

Park, et al. (1999) employed a GA optimizer with a mesoscopic simulator to optimize cycle length, green split, offset, and phase sequence of a hypothesized arterial system with low, medium, and high demand volume levels. The GA optimizer generated the first generation of individual signal plans randomly. The mesoscopic traffic simulator (an intermediate product of macroscopic and microscopic simulation with queue blocking effect modeling) evaluated average delay of each signal plan. Then the GA optimizer would evolve the next generation based on fitness values obtained from the simulator. The circulation process continued until the maximum generation number was reached. Compared with the solutions by TRANSYT-7F on the basis of a CORSIM simulation program, the solutions by GA had lower average delay under low and high demands and equivalent delay under medium demand.

In order to optimize signal control on mixed traffic arterials, Duerr (2000) used a GA with a microscopic traffic simulator as the fitness evaluator to minimize the performance index (PI) which considered vehicle behavior at intersections and transit stops. The optimization results of a seven-node arterial in Würzburg (Germany), temporal deviation of each phase duration from the standard setting at each node, showed that travel time dropped 25% and 5% for buses and cars respectively.

Furthermore, so as to optimize signal control under oversaturated traffic condition, Girianna and Benekohal (2002, 2004) applied a GA to a grid network of arterials. The optimization results of a hypothesized twenty-node network, green time of each phase at an intersection, showed that queues were successfully distributed spatially over different intersections and temporarily over different signal cycles.

Genetic Algorithms is one of the most suitable methods to solve problems with complex objective functions, large number of variables, and mixed solution space. Therefore, in this thesis, it is chosen to realize signal timing optimization for both pedestrians and vehicles.

Chapter 3

Development of Methodology for Signal Plan Optimization in a Single Intersection

Chapter 3 explicates total user time model, simple GA optimization procedure, geometric layout and basic signal plan in a hypothesized intersection.

3.1 Development of Total User Time Model

Section 3.1 explicates total user time model. Further detailed explanation about the calculation of two important variables in the model, average pedestrian and vehicle delay (D_p, D_v), is also included.

3.1.1 Total User Time

Section 3.1.1 explicates the total user time model. The model is mainly composed of two parts – total vehicle user time and total pedestrian user time. The detailed user time model is as follows.

$$UT = K \cdot T \cdot \frac{TD_p}{3600} + \sum_{i=1}^{12} [V(i) \cdot T \cdot \frac{D_v(i)}{3600} \cdot n_v]$$

If two-way crossing is applied, $TD_p = D_p(1) \cdot \sum_{j=1,3} P(j) + D_p(2) \cdot \sum_{j=2,4} P(j)$

If scramble crossing is applied, $TD_p = D_p(1) \cdot \sum_{j=1}^{4} P(j)$

Where UT = total user time in the analysis period (h)

T = duration of the analysis period (h)

K = relative time value of a pedestrian compared with a passenger car

TD_p = total pedestrian delay in the analysis period (s)

V(i) = vehicle adjusted volume in lane group i (veh/h)

$D_v(i)$ = average delay per passenger car in lane group i (s)

n_v = average vehicle occupancy per passenger car

$D_p(m)$ = average delay per pedestrian in pedestrian crossing direction m (s); for two-way crossing, $D_p(1)$ is for major street direction crossing, $D_p(2)$ is for minor street direction crossing; for scramble crossing, $D_p(1)$ is for crossing of all the directions.

P(j) = pedestrian volume of the pedestrian group j (ped/h)

According to the research of Ishaque, et al. (2007), the relative time value of a pedestrian compared with a passenger car (K) could range from 0 to 3 in most cases. Bhattacharya and Virkler (2005) recommended K value of 2. Therefore, one unit of pedestrian delay is set to equal two units of vehicle delay (K=2) in most of the tests in this thesis. In Section 6.4, the influence of different K values (K = 0, 1, 1.22, 2, and 3) on optimal signal plan would be discussed.

The average vehicle occupancy 1.22 (n_v = 1.22) is used in this study, on the basis of the traffic condition observation by Bhattacharya and Virkler (2005).

Furthermore, the vehicle adjusted volume (V) in the model equals to the hourly volume divided by a peak hour factor (PHF). The PHF is assumed to be 0.9 in the later part.

The notation of the lane group and pedestrian group indexes mentioned in this section is included Section 3.3.

3.1.2 Average Pedestrian Delay

Section 3.1.2 explicates the calculation of average delay per pedestrian in each pedestrian crossing direction.

The average pedestrian delay model is proposed in *Pedestrian Compliance Effects on Signal Delay* (Virkler, 1998). The model is based on the assumption that all pedestrians arrive randomly, which means pedestrians who arrive in green enter the intersection without any delay and pedestrian flow arrives uniformly in red. It is also assumed in the model that the cycle length is constant and no pedestrian actuation is applied in the intersection. The detailed model is as follows.

$$D_p = \frac{(R + 0.31A)^2}{2C} = \frac{[C - (G + 0.69A)]^2}{2C}$$

Where D_p = average delay per pedestrian (s)

R = duration of DONT WALK or red (s)

G = duration of WALK (s)

A = duration of flashing DONT WALK or clearance (s)

C = cycle length (s)

In addition, the model considers the compliance effect of pedestrians. In order to avoid waiting for the next WALK interval, certain pedestrians increase their waking speed and begin their crossing without a Walk indication. The majority of these phenomena happen during the flashing DONT WALK phase. According to Virkler's research (1998), 69 percent of pedestrians arriving at the curb during these periods will enter crosswalks. Therefore, 0.69 is used as an adjustment factor of pedestrian effective green time.

3.1.3 Average Vehicle Delay

Section 3.1.3 explicates the calculation of average delay per passenger car of each lane group. The average vehicle delay model is from HCM 2000. The detailed model is as follows.

$$D_v = d_1 + d_2 + d_3$$

$$d_2 = 900T[(X-1)+\sqrt{(X-1)^2+\frac{8kIX}{cT}}],$$

If $Q_b = 0$,

$$d_1 = PF\frac{0.5C(1-g/C)^2}{1-\min(1,X)g/C}, \quad d_3 = 0$$

$$t = \min\left[T, \frac{Q_b}{c(1-X)}\right], \quad u = \max\left[0, 1-\frac{cT}{Q_b}(1-X)\right]$$

If X<1, $Q_b > 0$,

$$d_1 = 0.5(C-g)\frac{t}{T} + PF\frac{0.5C(1-g/C)^2(T-t)}{(1-Xg/C)T}, \quad d_3 = \frac{1800Q_b(1+u)t}{cT}$$

If X≥1, $Q_b > 0$, $t = T$, $u = 1$

$$d_1 = 0.5(C-g), \quad d_3 = \frac{3600Q_b}{c}$$

Where D_v = average delay per passenger car(s/veh)

Q_b = initial queue at the start of period (veh)

PF = uniform delay progression adjustment factor

g = effective green time for lane group (s)

C = cycle length (s)

c = lane group capacity (veh/h) = sg/C

s = saturation flow rate (veh/h)

V = passenger car volume (veh/h)

X = V/c ratio = $(V \cdot C)/(s \cdot g)$

T = duration of the analysis period (h)

t = duration of unmet demand in T (h)

u = delay parameter

k = incremental delay factor (dependent on controller settings)

I = upstream filtering/metering adjustment factor

Furthermore, the following assumptions are made for the parameters related to this model:

- ✧ Considering that signals are coordinated on the major street (east-west direction), the Arrival Type (AT) of the lane groups on the major street are presumed to be 4 (favorable progression quality), while the others to be 3 (random arrivals).
- ✧ Progression adjustment factor (PF) is constant (1) on the minor street, and equals to (1-1.333*g/C)*1.15/(1-g/C) on the major street. Since PF should not exceed 1 for AT 4, PF is considered to be 1 if the calculation result is larger than 1.
- ✧ Upstream degree of saturation (X_u) equals to 0.8 for each approach.
- ✧ Upstream filtering adjustment factor (I) is 0.5 for each approach according to exhibit 15-7 in HCM 2000.
- ✧ Since the traffic signals discussed in this thesis are non-actuated, incremental delay factor (k) is constant (0.5) according to exhibit 15-6 in HCM 2000.

As for saturation flow rates, the detailed calculation procedure from HCM 2000 is as follows.

$$s = s_o N f_a f_{LT} f_{RT} f_{Lpb} f_{Rpb},$$

Where s = saturation flow rate for subject lane group, expressed as a total for all lanes in lane group (veh/h)

s_o = base saturation flow rate per lane (veh/h/ln)

N = number of lanes in lane group

f_a = adjustment factor for area type, its value is set at 0.9 since CBD is discussed in this thesis

f_{LT} = adjustment factor for left turns in lane group

f_{RT} = adjustment factor for right turns in lane group

$f_{Lpb} = 1 - P_{LT}(1 - A_{pbT})(1 - P_{LTA})$ = pedestrian adjustment factor for left-turn movements

$f_{Rpb} = 1 - P_{RT}(1 - A_{pbT})(1 - P_{RTA})$ = pedestrian adjustment factor for right-turn movements

P_{LT} = proportion of LTs in lane group;

P_{RT} = proportion of RTs in lane group

A_{pbT} = permitted phase adjustment

P_{LTA} = proportion of LTs using protected phase

P_{RTA} = proportion of RTs using protected phase

The base saturation flow rate per lane of left-turn, through, and right-turn movement are set at 1800, 1800, and 1800 (veh/h/ln), considering lower approach speeds due to pedestrian inference.

According to the hypothesized intersection layout and the basic signal plan setting in Section 3.3, the setting of factors related to saturation flow rate calculation is listed in Table 3.1.

Table 3.1 The Setting of Factors Related to Saturation Flow Rate Calculation and the Equations for the Saturation Flow Rates in the Hypothesized Intersection

	Left-Turn Lane Group	Through Lane Group	Right-Turn Lane Group
N	1	1	1
f_a	0.9	0.9	0.9
f_{LT}	0.95	1	-
f_{RT}	-	1	0.85
f_{Lpb}	1	1	-
f_{Rpb}	-	1	Two-way: if $P_p \leq 1$, $(1-0.6*OCC_r)*P_p+(1-P_p)$ else $(1-0.6*OCC_r^{'})$ Scramble: 1
s (veh/h/ln)	1800*0.9*0.95	1800*0.9	Two-way: 1800*0.9*0.85*$[(1-0.6*OCC_r)*P_p+(1-P_p)]$ Scramble: 1800*0.9*0.85

Notes:

1.For Left-Turn Lane Group, P_{LT} *=1,* P_{LTA} *=1. For Right-Turn Lane Group,* P_{RT} *=1,* P_{RTA} *=0,* $OCC_r = OCC_{pedg}$. *Since* $N_{rec} = 2 > N_{tum} = 1$, $A_{pbT} = 1-0.6*OCC_r$.

2. P_p *= Proportion of pedestrian green time (*g_p*) in the vehicle effective green time*

$OCC_r^{'}$ *= average pedestrian occupancy calculated with* g_p *equivalent to vehicle green time*

$$v_{pedg} = v_{ped} * C / g_p$$

If $v_{pedg} \le 1000$, $OCC_{pedg} = v_{pedg} / 2000$

If $1000 < v_{pedg} \le 5000$, $OCC_{pedg} = 0.4 + v_{pedg} / 10000$

Where OCC_{pedg} = average pedestrian occupancy

v_{pedg} = pedestrian volume in a one-hour green interval (ped/h),

v_{ped} = pedestrian flow rate (ped/h)

g_p = pedestrian green time, both WALK and DONT WALK (s)

3.2 Simple Genetic Algorithm Optimization Procedure

Section 3.2 explicates chromosome structure, searching space, GA operators, value of critical GA parameters, and simple GA optimization procedure.

3.2.1 Chromosome Structure and Searching Space

The individual would be defined as the characteristics of a signal plan. The basic variables of the signal plan are encoded into a chromosome. Such basic variables include as follows.

Flag = binary index of pedestrian crossing pattern,

0 for two-way crossing, 1 for scramble crossing

G = duration of WALK phases (s), G(1) for major street direction crossing, G(2) for minor street direction crossing

g = effective green time for vehicle lane group (s), an array with 4 items in the order of g(2), g(5), g(1), g(4)

The chromosome of the individual stores the binary code of all the basic variables sequentially. The increment step of each variable is 1, which means all these basic variables in the chromosome are integers. The detailed setting of each basic variable in the chromosome is listed in Table 3.2.

Table 3.2 The Setting of the Basic Variables in the Chromosome

Variable	Range	Number of Bits	Expression of Binary Decode (BD)
Flag	0-1	1	BD
G (Seconds)	Scramble: G(1) 0, 4-35, G(2) 0 Two-way: G(1) 0, 4-35, G(2) 0, 4-35	array(2), with 5 bits for each item	0, BD+4; 0 0, BD+4
g (Seconds)	g(1), g(4) 0, 7-21 g(2), g(5) 10-41	array(4), with 5 bits for each item	0, fix(BD/2)+6 BD+10

Based on the chromosome structure, the searching space of this signal plan optimization problem can be calculated. If two-way crossing is applied, there are 6 variables for each solution, i.e. G(1) (32 possible values), G(2) (32 possible values), g(1) (16 possible values), g(4) (16 possible values), g(2) (32 possible values), and g(5) (32 possible values). If scramble crossing is applied, there are 5 variables for each solution, i.e. G(1) (32 possible values), g(1) (16 possible values), g(4) (16 possible values), g(2) (32 possible values), and g(5) (32 possible values).

Therefore, the total probable solutions in the searching space

= (number of solutions if scramble)*(number of solutions if two-way)

= (32*32) *(16*16*32*32) + 32*(16*16*32*32) = *276,824,064*.

Due to GA's excellent capability to find suitable solutions in a very large mixed solution space, the Genetic Algorithm would be one of the best methods to solve this signal optimization problem.

The notation of the lane group and pedestrian group indexes mentioned in this section is included Section 3.3.

3.2.2 GA Operators and Critical GA Parameters

GA Operators employed in the proposed optimization procedure are as follows.

- Pairwise tournament selection without replacement
- Mutation
- Single point crossover

The setting of critical GA parameters is as follows.

- Crossover probability = 50%, since the tournament selection is pairwise.
- Mutation probability = 3.23%, since this probability would maintain minimum diversity in the population and successful local search.
- Population Size = 31.

  Population size has to be larger than or equal to chromosome length, so that minimum diversity in the population and successful local search can be both maintained. Moreover, the chromosome length is 31 according to the chromosome structure shown in Section 3.2.1. Thus, the population size is set as its minimal value (31).

✧ Maximum number of generations = 50. Refer to Section 5.2.

3.2.3 Simple GA Optimization Procedure

Three kinds of variables are required as the input of the GA optimization procedure.

✧ vehicle volume of each movement (veh/h)

✧ pedestrian volume of each direction (ped/h)

✧ initial queue of each lane group at the start of the analysis period (veh)

Except for the basic variables in the chromosome that are carried by each individual, individuals also have other variables deduced either from the basic variables or by other logics. Such variables include as follows.

A_v= duration of yellow change intervals

AR = duration of red clearance intervals

C = cycle length

g = effective green time for vehicle lane groups which are not defined in the chromosome of the individual (g(3), g(6)~g(12))

The detailed setting of the other critical variables carried by each individual is listed in Table 3.3.

Table 3.3 The Setting of Other Critical Variables Carried by Each Individual

Variable	Calculation Procedure
A_v	3 seconds for each phase
AR	Scramble: 2 seconds for the pedestrian phase 1 second for each vehicle left-turn and through phase Two-way: 2 seconds for either the through vehicle or pedestrian phases (depending on which phase is longer) 1 second for each left-turn vehicle phase
C	Scramble: C=G(1)+A(1)+A_v+g(1)+g(2)+g(4)+g(5)+AR Two-way: If g(2)>=G(1)+A(1) Temp1=g(1)+g(2) Else Temp1= G(1)+A(1)+g(1) If g(5)>=G(2)+A(2) Temp2= g(4)+g(5) Else Temp1= G(2)+A(2)+g(4) C=Temp1+Temp2+A_v+AR
g	Calculated form g(2), g(5), g(1), and g(4) by assuming that the opposite direction effective green time is equal to each other and that right turn effective green time is equal to the green time of the through movement in the same approach.

Furthermore, duration of flashing DONT WALK phases (A) is another critical variable carried by each individual. In order to ensure that the pedestrians, who step into an intersection just when a WALK phase changes into a flashing DONT WALK, can cross the intersection safely, average crossing time is used to set the duration of flashing DONT WALK phases. The duration of flashing DONT WALK phases for a two-way crossing intersection is calculated based on the following equation.

$$A(i) = \frac{L(i)}{S_p}$$

Where A = duration of flashing DONT WALK phases (s); A(1) for major street direction crossing, A(2) for minor street direction crossing

L = crosswalk length (ft); L(1) for major street direction crossing, L(2) for minor street direction crossing; if the opposing approaches don't have the same crosswalk length, the longer crosswalk length is applied in the calculation.

S_p = average pedestrian speed, set as 15th-percentile pedestrian speed (4 ft/s).

The duration of flashing DONT WALK phases for a scramble crossing intersection is calculated in the same method, except for that the crosswalk length is the longer one in the diagonal directions. With regard to the calculation of crosswalk length, it is acquired based on the geometric layout of the intersection, e.g. lane width, number of lanes.

According to the geometric layout of the hypothesized intersection (Figure 3.2), duration of flashing DONT WALK phases is constant if the same kind of pedestrian crossing is applied. If scramble crossing is applied, A(1) = 17 seconds, while G(2) and A(2) are set as zeroes since there is only one phase for pedestrians. If two-way crossing is applied, A(1) = A(2) = 12 seconds. The pedestrian phase setting procedure, including both flashing DONT WALK and WALK phases, refers to the description in *Scramble and Crosswalk Signal Timing* (Virkler, 1998), MUTCD 2003, and *Signal Timing on a Shoestring* (Henry, 2009).

Moreover, duration of WALK phases is required to be reset, if the total duration of a WALK phase and a flashing DONT WALK phase is smaller than pedestrian minimum green time ($G + A < G_p$). The amount of increment needed for the WALK phase duration is the difference between pedestrian minimum green time and average crossing time ($G = G_p - A$).

Pedestrian minimum green time is the largest calculation result of the following equation in all the right-of-way directions. The minimum pedestrian green time model as follows is from HCM 2000.

$$G_p = 3.2 + \frac{L}{S_p} + 0.27 N_{ped}$$

Where G_p = minimum green time (s)

3.2= pedestrian start-up time (s)

N_{ped} = number of pedestrians crossing during an interval

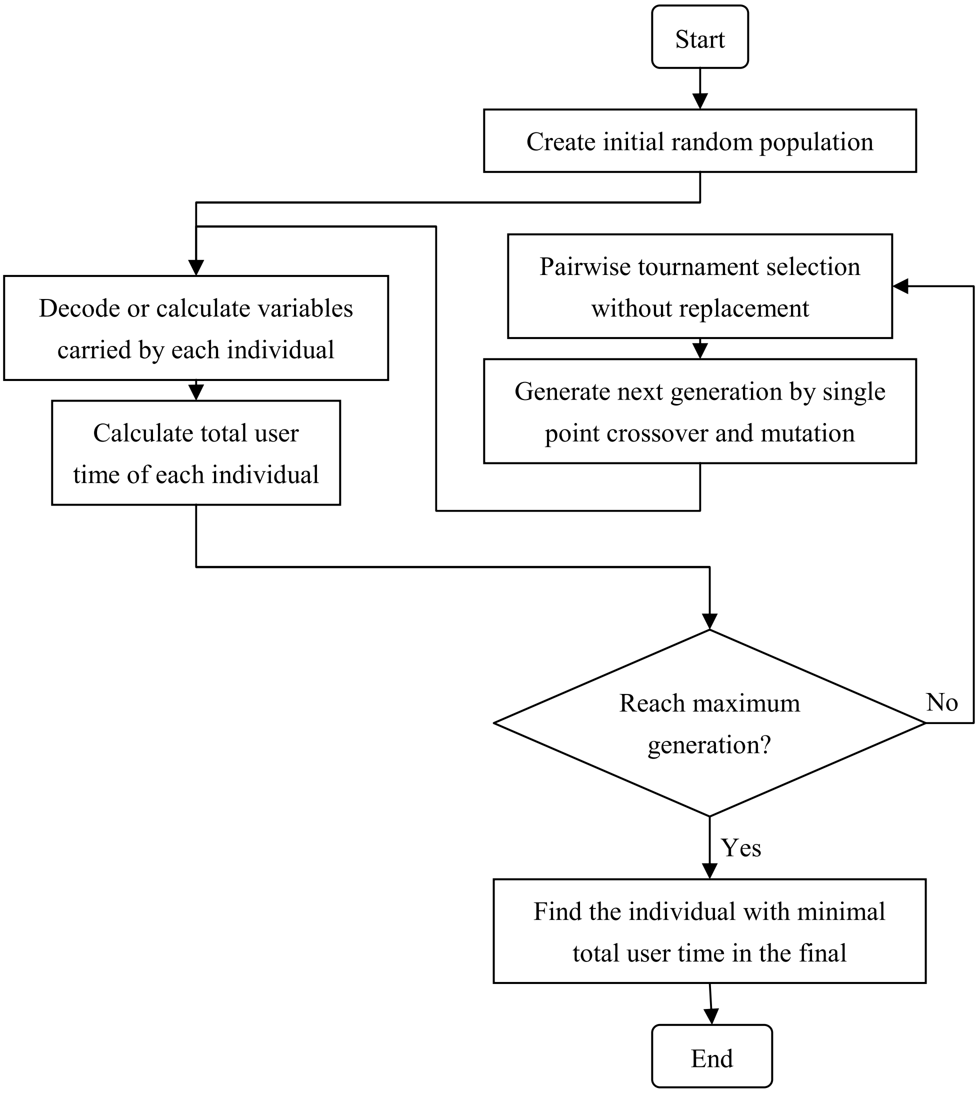
L = crosswalk length (ft)

S_p = average pedestrian speed, set as 4 ft/s.

If two-way crossing is applied, both eastbound and westbound (or both northbound and westbound) green time should be calculated to compare with each other. If scramble crossing is applied, all of four bounds and both diagonal directions are required to be calculated.

Based on all of the logics illustrated above, GA optimization procedure can be run. The brief flowchart of the procedure is shown in Figure 3.1.

Figure 3.1 Brief Flowchart of GA Optimization Procedure



The procedure result would be the proposed signal plan for the hypothesized intersection. The procedure determines whether each phase would be displayed and optimizes each phase length. However, the phase types and sequence of the basic signal plan (Figure 3.3) would not be changed. In addition, the actual green time for the signal plan can be consider to equal the effective green time from the GA optimization result, because start-up lost time and extension of effective green time are both assumed to be 2 seconds for all the lane groups.

The notation of the lane group and pedestrian group indexes mentioned in this section is included Section 3.3.

3.3 Geometric Layout and Basic Signal Plan of a Hypothesized Intersection

In order to verify the optimization procedure, an intersection is hypothesized to test the effectiveness of the procedure in different scenarios. There are one receiving lane and three exclusive lanes for left-turn, through, and right-turn traffic in each approach to enter into the intersection. The layout and basic signal plan of the hypothesized intersection are illustrated respectively in Figures 3.2 and 3.3.

Figure 3.2 The Diagram of the Hypothesized Intersection

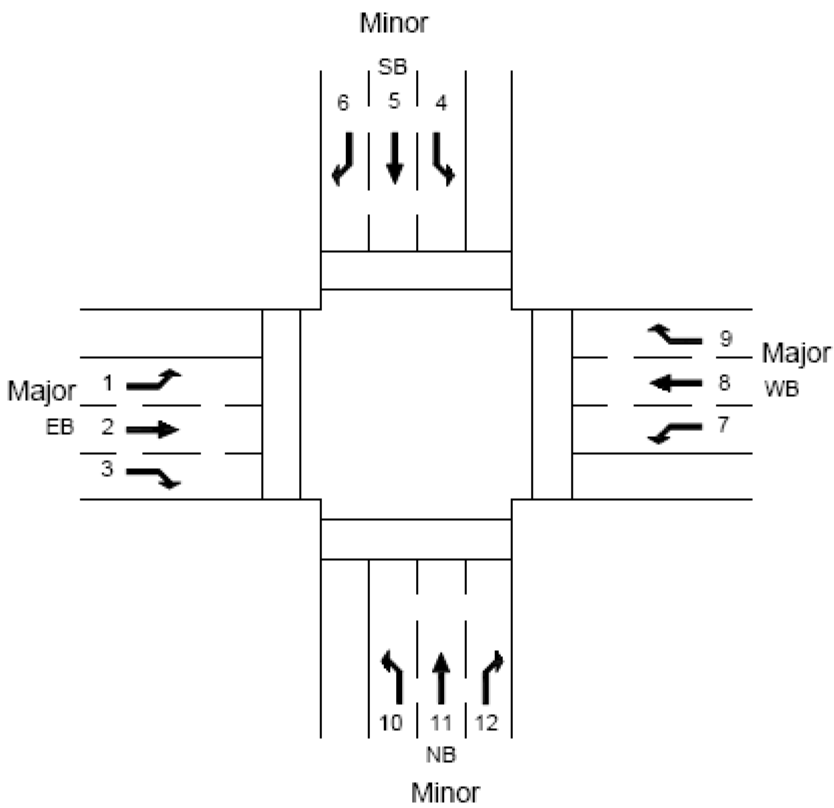
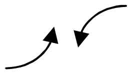
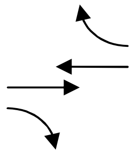
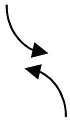
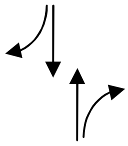
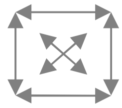
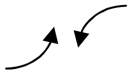
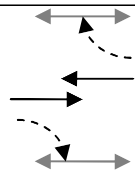
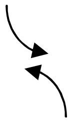
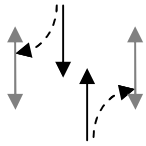


Figure 3.3 The Basic Signal Plan of the Hypothesized Intersection

Length of the Phase	g(1)	g(2)	g(4)	g(5)	G(1)+A(1)
Scramble Crossing Signal Plan					 Scramble
Two-Way Crossing Signal Plan					–

Furthermore, the following assumptions are made in the intersection geometric layout and traffic pattern:

- ✧ All the lane widths are equal to 12 feet.
- ✧ All the effective crosswalk widths are equal to 10 feet.
- ✧ The intersection is located in a central business district.
- ✧ Pedestrian crossing is not allowed during a protected left-turn phase.
- ✧ No bicycle traffic flow exists.
- ✧ No turn on red is allowed for right-turn vehicles. This assumption is made because the intersection is located in the central business district which means heavy competing traffic and pedestrian flow might barely give enough gaps for right-turn vehicles.

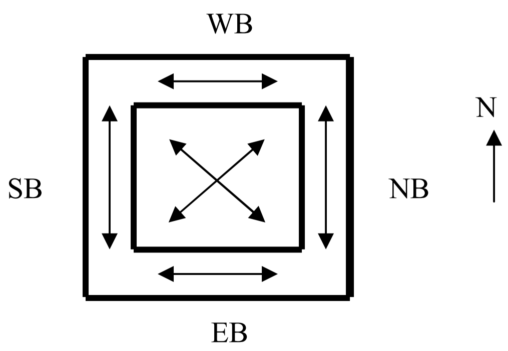
In other sections of this thesis, all the lane groups and pedestrian groups are numbered to simplify their expression. The indexes of each lane group and pedestrian group are respectively listed in Tables 3.4 and 3.5.

Table 3.4 The Index of Each Lane Group

Lane Group (assume major street E-W direction)	Index of the Lane Group
Eastbound left	1
Eastbound through	2
Eastbound right	3
Southbound left	4
Southbound through	5
Southbound right	6
Westbound left	7
Westbound through	8
Westbound right	9
Northbound left	10
Northbound through	11
Northbound right	12

Table 3.5 The Index and Definition of Each Pedestrian Group

Pedestrian Group	Index of the Pedestrian Group
Eastbound	1
Southbound	2
Westbound	3
Northbound	4



Chapter 4

Verification of the Optimization Procedure

In Chapter 4, to verify the proposed GA optimization procedure, 10 tests are run from five aspects, including vehicle aspect, pedestrian aspect, vehicle and pedestrian integration aspect, and total user time aspect. Each test has at least 3 cases to support the evaluation.

Each case is run by 5 different random seeds. Each random seed is required to be an odd four-digit random number between 1000 and 9999. Therefore, 1347, 9045, 9693, 7311, and 6153 are chosen from a random number table on the World Health Organization website. The starting point is column 13, row 1, and the reading direction is up to down, left to right. In the following sections, in order to simplify the notation, random seeds (1347, 9045, 9693, 7311, and 6153) are represented by Random Seed #1, #2, #3, #4 and #5 respectively. In addition, the number of random seeds is chosen to be 5, because the results are close to each other and their deviation is very small.

Furthermore, considering most of the time neither vehicle nor pedestrian volume would rise or drop significantly in a relatively short period, the analysis period of each case in Chapter 4 is set as 15 minutes (T=0.25).

Moreover, if the scramble crossing is applied, the percentage of pedestrians who cross in diagonal directions is one of the inputs of the program. It is set as 33.3%, because the probability that a pedestrian chooses every moving direction is assumed to be equal.

Additionally, to simplify the input procedure for each case, initial queues (Q_b) are assumed to be 0 for all the movements, if none of the hourly volumes is larger than or equal to 600 (veh/h). Otherwise, there would be 5 (veh) unmet demand for each left or right movement and 10 (veh) unmet demand for each through movement.

4.1 Vehicle Aspect Verification

Verification in Section 4.1 includes tests of scenarios with variable left-turn volumes, scenarios with variable through or right-turn volumes, and scenarios with variable left-turn and through volumes.

4.1.1 Scenarios with Variable Left-Turn Volumes

The left-turn phase duration of a reasonable signal plan should reflect the impact of the corresponding left-turn volume(s). The duration should be raised with the growth of the corresponding left-turn volume, if the movement is critical. Additionally, no left-turn phase is needed if there is no corresponding left-turn traffic.

Cases 1 to 3 are run to verify the impact of the left-turn volume on signal plans. As an example, the eastbound left-turn volume, V(1), is varied in this section. V(1) would increase from 0 to 400 (veh/h) with an increment of 200 (veh/h), while the other volumes remain stable. Table 4.1 lists the detailed settings of hourly vehicle volumes (V) and pedestrian volumes (P) of Cases 1 to 3.

Table 4.1 Setting of Hourly Vehicle (veh/h) and Pedestrian Volumes (ped/h) in Cases 1 to 3

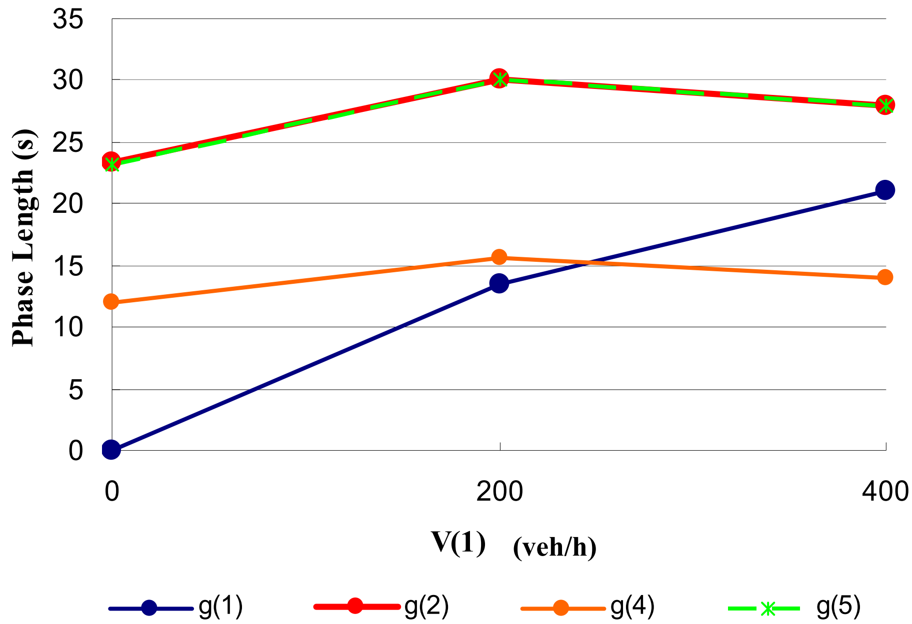
V(1)	**V(2)**	**V(3)**	**V(4)**	**V(5)**	**V(6)**	**P(1)**	**P(2)**
[0, 200, 400]	400	200	200	400	200	0	0
V(7)	**V(8)**	**V(9)**	**V(10)**	**V(11)**	**V(12)**	**P(3)**	**P(4)**
0	400	200	200	400	200	0	0

Table 4.2 Optimization Results of g(1), g(2), g(4), g(5) and C in Cases 1 to 3

Case		**1**	**2**	**3**
V(1)		***0***	***200***	***400***
Random Seed #1	***g(1)***	0	13	21
	g(2)	22	29	28
	g(4)	12	15	14
	g(5)	22	29	28
	C	70	104	109
Random Seed #2	***g(1)***	0	13	21
	g(2)	21	30	29
	g(4)	11	15	15
	g(5)	21	29	29
	C	67	105	112
Random Seed #3	***g(1)***	0	13	21
	g(2)	22	30	28
	g(4)	11	16	14
	g(5)	21	30	28
	C	68	107	109
Random Seed #4	***g(1)***	0	15	21
	g(2)	26	32	28
	g(4)	13	17	14
	g(5)	26	32	28
	C	79	114	109
Random Seed #5	***g(1)***	0	13	21
	g(2)	26	29	27
	g(4)	13	15	13
	g(5)	26	30	27
	C	79	105	106

Note: All the data are in the unit of seconds.

Figure 4.1 Expected Values of Optimal g(1), g(2), g(4) and g(5) in Cases 1 to 3



The phase plans selected by the GA procedure are reasonable. Since there is no westbound left-turn traffic, the eastbound left-turn traffic is the critical movement of the left-turn phase along the major street. According to Cases 1 to 3, the duration of the left-turn phase along the major street, g(1), increases significantly with V(1)'s increment. In addition, Case 1 is a special case that no left turn is allowed along the major street, which means that there is neither eastbound nor westbound left-turn traffic. In such a situation, the GA procedure selects the signal plans that have no left-turn phase along the major street (g(1)=0). Table 4.2 lists the detailed running results of signal plans by the GA procedure, and Figure 4.1 illustrates the expected values of optimal g(1), g(2), g(4) and g(5) in Cases 1 to 3.

4.1.2 Scenarios with Variable Through or Right-Turn Volumes

Since only the permitted right-turn phase is applied in the hypothesized intersection, the impact object of various right-turn volumes on signal plans is the same as that of various through volumes, which is the through phase.

The through phase duration of a reasonable signal plan should reflect the impact of the corresponding through or right-turn volume(s). The duration should be raised with the growth of the corresponding through or right-turn volume, if the movement is critical.

Cases 4 to 7 are run to verify the impact of the through volume on signal plans. As an example, the eastbound through volume, V(2), is varied in this section. V(2) would increase from 200 to 800 (veh/h) with an increment of 200 (veh/h), while the other volumes remain stable. Table 4.3 lists the detailed settings of hourly vehicle volumes (V) and pedestrian volumes (P) of Cases 4 to 7.

Table 4.3 Setting of Hourly Vehicle (veh/h) and Pedestrian Volumes (ped/h) in Cases 4 to 7

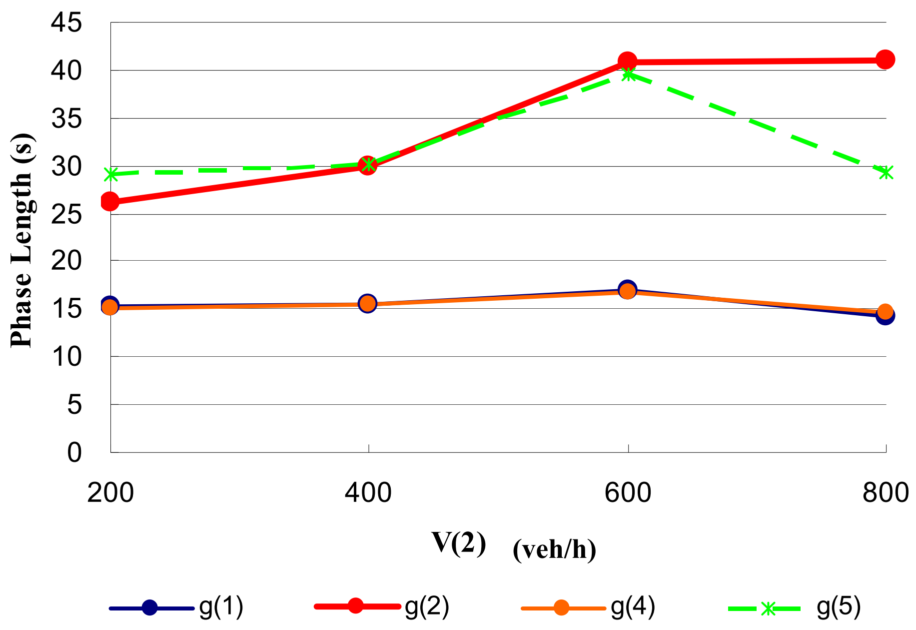
V(1)	**V(2)**	**V(3)**	**V(4)**	**V(5)**	**V(6)**	**P(1)**	**P(2)**
200	[200, 400, 600, 800]	200	200	400	200	0	0
V(7)	**V(8)**	**V(9)**	**V(10)**	**V(11)**	**V(12)**	**P(3)**	**P(4)**
200	400	200	200	400	200	0	0

Table 4.4 Optimization Results of g(1), g(2), g(4), g(5) and C in Cases 4 to 7

Case		**4**	**5**	**6**	**7**
V(2)		***200***	***400***	***600***	***800***
Random Seed #1	***g(1)***	13	13	17	14
	g(2)	22	27	41	41
	g(4)	13	14	17	13
	g(5)	25	27	40	28
	C	91	99	133	114
Random Seed #2	***g(1)***	18	16	17	14
	g(2)	31	32	41	41
	g(4)	18	16	17	15
	g(5)	34	32	40	30
	C	119	114	133	118
Random Seed #3	***g(1)***	16	18	17	14
	g(2)	27	34	41	41
	g(4)	16	17	17	15
	g(5)	30	34	39	30
	C	107	121	132	118
Random Seed #4	***g(1)***	15	15	17	14
	g(2)	27	28	40	41
	g(4)	15	15	16	15
	g(5)	30	29	39	30
	C	105	105	130	118
Random Seed #5	***g(1)***	14	15	17	15
	g(2)	24	29	41	41
	g(4)	13	15	17	15
	g(5)	26	29	40	29
	C	95	106	133	118

Note: All the data are in the unit of seconds.

Figure 4.2 Expected Values of Optimal g(1), g(2), g(4) and g(5) in Cases 4 to 7



The phase plans selected by the GA procedure are reasonable. Based on the 12 different volumes in the intersection, the westbound through traffic is the critical movement of the through phase along the major street in Cases 4, and the eastbound through traffic is critical in Case 5 to 7. The duration of the through phase along the major street, g(2), increases relatively gently with V(2)'s increment from 200 to 400. However, g(2) increases relatively significantly with V(2)'s increment from 400 to 600. Moreover, according to Case 7, after g(2) reaches its 41-second upper limit (refer to Section 3.2.1) with lower V(2) (like in Case 6), g(2) would remain stable at its maximum even with higher V(2). Table 4.4 lists the detailed running results of signal plans by the GA procedure, and Figure 4.2 illustrates the expected values of optimal g(1), g(2), g(4) and g(5) in Cases 4 to 7.

Cases 5, 8 and 9 are run to verify the impact of the right-turn volume on signal plans. As an example, the eastbound right-turn volume, V(3), is varied in this section. V(3) would increase from 200 to 600 (veh/h) with an increment of 200 (veh/h), while the other volumes remain stable. Table 4.5 lists the detailed settings of hourly vehicle volumes (V) and pedestrian volumes (P) of Cases 5, 8, and 9.

Table 4.5 Setting of Hourly Vehicle (veh/h) and Pedestrian Volumes (ped/h) In Cases 5, 8, & 9

V(1)	**V(2)**	**V(3)**	**V(4)**	**V(5)**	**V(6)**	**P(1)**	**P(2)**
200	400	[200, 400, 600]	200	400	200	0	0
V(7)	**V(8)**	**V(9)**	**V(10)**	**V(11)**	**V(12)**	**P(3)**	**P(4)**
200	400	200	200	400	200	0	0

Table 4.6 Optimization Results of g(1), g(2), g(4), g(5) and C in Cases 5, 8, & 9

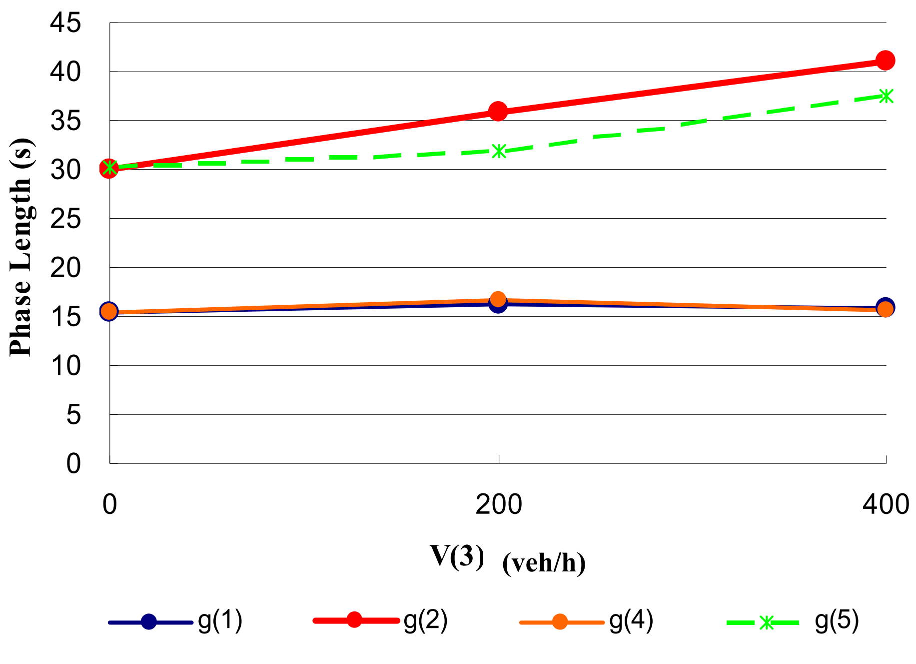
Case		**5**	**8**	**9**
V(3)		***200***	***400***	***600***
Random Seed #1	***g(1)***	13	16	16
	g(2)	27	36	41
	g(4)	14	17	15
	g(5)	27	32	37
	C	99	119	127
Random Seed #2	***g(1)***	16	16	16
	g(2)	32	36	41
	g(4)	16	17	15
	g(5)	32	32	37
	C	114	119	127
Random Seed #3	***g(1)***	18	17	15
	g(2)	34	36	41
	g(4)	17	16	16
	g(5)	34	32	37
	C	121	119	127

Table 4.6 (cont.)

Random Seed #4	***g(1)***	15	16	16
	g(2)	28	36	41
	g(4)	15	17	16
	g(5)	29	32	38
	C	105	119	129
Random Seed #5	***g(1)***	15	16	16
	g(2)	29	35	41
	g(4)	15	16	16
	g(5)	29	31	38
	C	106	116	129

Note: All the data are in the unit of seconds.

Figure 4.3 Expected Values of Optimal g(1), g(2), g(4) and g(5) in Cases 5, 8, & 9



The phase plans selected by the GA procedure are reasonable. Based on the 12 different volumes in the intersection, the eastbound through traffic is the critical movement of the through phase along the major street in Cases 5, and the eastbound right-turn traffic is critical in Cases 8 and 9. The duration of the through phase along the major street, g(2), increases relatively gently with V(2)'s increment from 200 to 400. However, g(2) increases relatively significantly with V(2)'s increment from 400 to 600. Table 4.6 lists the detailed running results of signal plans by the GA procedure, and Figure 4.3 illustrates the expected values of optimal g(1), g(2), g(4) and g(5) in Cases 5, 8, and 9.

4.1.3 Scenarios with Variable Left-Turn and Through Volumes

A reasonable signal plan should also be able to reflect the combined impact of the corresponding left-turn and through volumes. The relevant durations should be raised with the growth of the corresponding left-turn and through volumes, if the movements are critical.

Cases 10, 5 and 11 are run to verify the combined impact of the left-turn and through volumes on signal plans. As an example, the eastbound left-turn volume, V(1), and through volume, V(2), are both varied in this section. V(1) would increase from 0 to 400 (veh/h) with an increment of 200 (veh/h) and V(2) from 200 to 600 (veh/h) with the same increment, while the other volumes remain stable. Table 4.7 lists the detailed settings of hourly vehicle volumes (V) and pedestrian volumes (P) of Cases 10, 5, and 11.

Table 4.7 Setting of Hourly Vehicle (veh/h) and Pedestrian Volumes (ped/h)

In Cases 10, 5, & 11

V(1)	**V(2)**	**V(3)**	**V(4)**	**V(5)**	**V(6)**	**P(1)**	**P(2)**
[0, 200, 400]	[200, 400, 600]	200	200	400	200	0	0
V(7)	**V(8)**	**V(9)**	**V(10)**	**V(11)**	**V(12)**	**P(3)**	**P(4)**
200	400	200	200	400	200	0	0

Table 4.8 Optimization Results of g(1), g(2), g(4), g(5) and C in Cases 10, 5, & 11

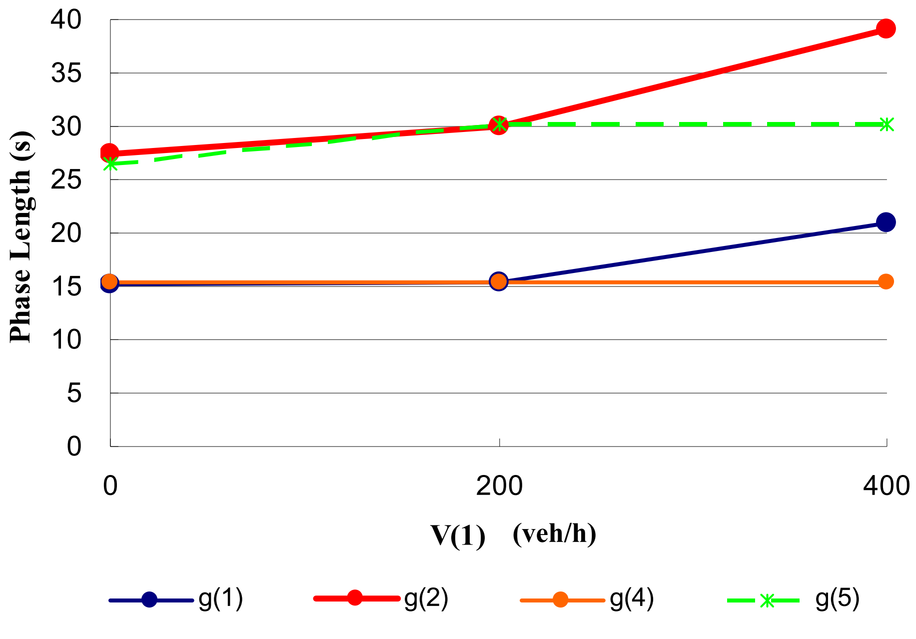
Case		**10**	**5**	**11**
V(1), V(2)		***0, 200***	***200, 400***	***400, 600***
Random Seed #1	***g(1)***	13	13	21
	g(2)	26	27	39
	g(4)	15	14	15
	g(5)	29	27	31
	C	101	99	124
Random Seed #2	***g(1)***	16	16	21
	g(2)	34	32	39
	g(4)	18	16	16
	g(5)	35	32	30
	C	121	114	124
Random Seed #3	***g(1)***	12	18	21
	g(2)	24	34	39
	g(4)	13	17	15
	g(5)	26	34	30
	C	93	121	123
Random Seed #4	***g(1)***	14	15	21
	g(2)	27	28	39
	g(4)	16	15	15
	g(5)	30	29	30
	C	105	105	123
Random Seed #5	***g(1)***	21	15	21
	g(2)	26	29	39
	g(4)	15	15	16

Table 4.8 (cont.)

Random Seed #5	***g(5)***	12	29	30
	C	92	106	124

Note: All the data are in the unit of seconds.

Figure 4.4 Expected Values of Optimal g(1), g(2), g(4) and g(5) in Cases 10, 5, & 11



The phase plans selected by the GA procedure are reasonable. Based on the 12 different volumes in the intersection, the westbound left-turn traffic and through traffic are the critical movements of the left-turn and through phases along the major street in Cases 10, and the eastbound left-turn traffic and through traffic are critical in Cases 5 and 11. The durations of the left-turn and through phases along the major street, g(1) and g(2), increase relatively gently with V(1)'s increment from 0 to 200 and V(2)'s from 200 to 400. However, g(1) and g(2) increase relatively significantly with and V(1)'s increment from 200 to 400 and V(2)'s from 400 to 600. Table 4.8 lists the detailed running results of signal plans by the GA procedure, and Figure 4.4 illustrates the expected values of optimal g(1), g(2), g(4) and g(5) in Cases 10, 5, and 11.

4.2 Pedestrian Aspect Verification

Verification in Section 4.2 includes tests of scenarios with variable pedestrian volumes and scenarios with variable opposing pedestrian volumes.

4.2.1 Scenarios with Variable Pedestrian Volumes

The duration of WALK phase in a reasonable signal plan should reflect the impact of the corresponding pedestrian volume(s). The duration should be raised with the growth of the corresponding pedestrian volume, if the movement is critical. Additionally, neither WALK nor flashing DONT WALK phase is needed if there is no corresponding pedestrian flow.

Furthermore, the type of pedestrian crossing in a reasonable signal plan should reflect the impact of the corresponding pedestrian volume(s). The type should be changed from two-way crossing to scramble crossing with enormous growth of the corresponding pedestrian volume.

Cases 12 to 17 are run to verify the impact of the pedestrian volume on signal plans. As an example, the eastbound pedestrian volume, P(1), is varied in this section. P(1) would increase from 200 to 4200 (ped/h) with an increment of 800 (ped/h), while the other volumes remain stable. Table 4.9 lists the detailed settings of hourly vehicle volumes (V) and pedestrian volumes (P) of Cases 12 to 17.

Table 4.9 Setting of Hourly Vehicle (veh/h) and Pedestrian Volumes (ped/h) in Cases 12 to 17

V(1)	**V(2)**	**V(3)**	**V(4)**	**V(5)**	**V(6)**	**P(1)**	**P(2)**
200	400	200	200	400	200	[200, 1000, 1800, 2600, 3400, 4200]	200
V(7)	**V(8)**	**V(9)**	**V(10)**	**V(11)**	**V(12)**	**P(3)**	**P(4)**
200	400	200	200	400	200	200	200

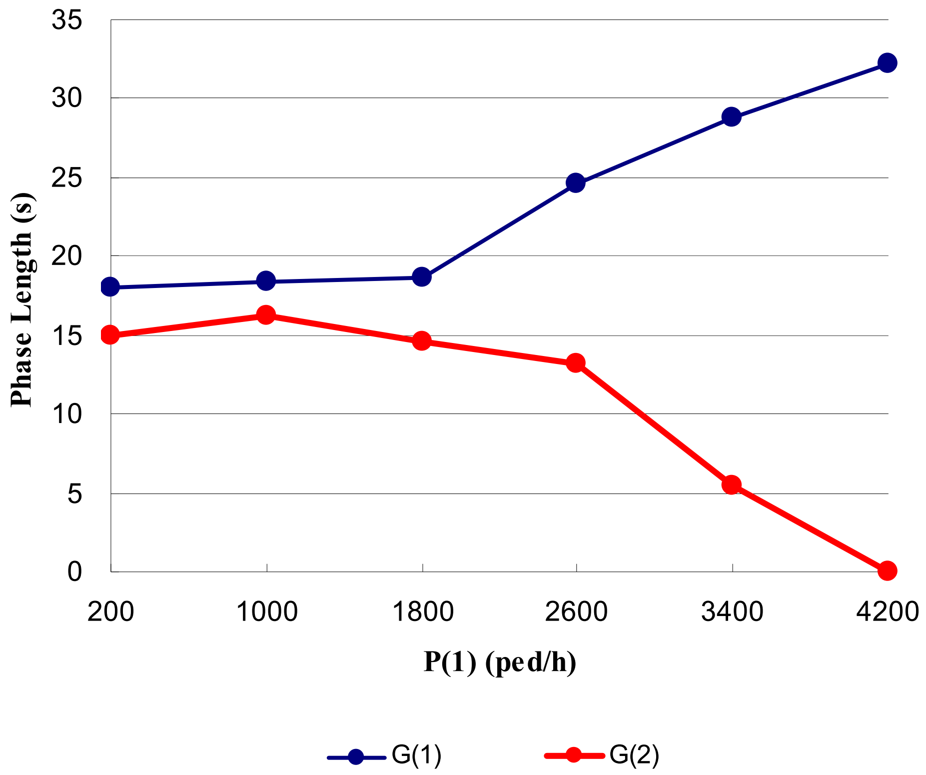
Table 4.10 Optimization Results of Flag, G(1), G(2), and C in Cases 12 to 17

Case		**12**	**13**	**14**	**15**	**16**	**17**
P(1)		***200***	***1000***	***1800***	***2600***	***3400***	***4200***
Random Seed #1	***Flag***	0	0	0	0	0	1
	G(1)	16	18	23	24	31	33
	G(2)	10	18	17	10	9	0
	C	100	114	114	109	110	168
Random Seed #2	***Flag***	0	0	0	0	0	1
	G(1)	20	19	18	24	29	33
	G(2)	10	13	15	15	5	0
	C	116	112	112	107	103	168
Random Seed #3	***Flag***	0	0	0	0	1	1
	G(1)	19	16	17	25	26	32
	G(2)	20	17	13	15	0	0
	C	117	109	105	112	166	163
Random Seed #4	***Flag***	0	0	0	0	1	1
	G(1)	17	19	18	24	24	32
	G(2)	18	18	14	14	0	0
	C	115	110	106	105	154	163
Random Seed #5	***Flag***	0	0	0	0	0	1
	G(1)	18	20	17	26	34	31
	G(2)	17	15	14	12	13	0
	C	112	105	100	115	119	158

Notes: 1. Except for the variable Flag, all the data are in the unit of seconds.

2. A case listed with gray shade is suggested to apply scramble crossing by the proposed GA optimization procedure

Figure 4.5 Expected Values of Optimal G(1) and G(2) in Cases 12 to 17



The phase plans selected by the GA procedure are reasonable. Based on the 4 different pedestrian volumes in the intersection, the eastbound pedestrian flow is the critical movement of the WALK phase along the major street in Cases 12 to 17. According to Cases 12 to 17, the duration of the WALK phase along the major street, G(1), increases significantly with P(1)'s increment. Table 4.10 lists the detailed running results of signal plans by the GA procedure, and Figure 4.5 illustrates the expected values of optimal G(1) and G(2) in Cases 12 to 17.

Furthermore, the type of pedestrian crossing selected by the GA procedure is reasonable. The type of the WALK phase along the major street start to change from two-way crossing to scramble crossing after P(1) increases from 2600 to 3400 (ped/h).

In addition, Cases 1 to 11 (in Section 4.1) are actually special cases that there is no pedestrian flow along both the major and minor streets. In such situations, the GA procedure selects the signal plans that have neither WALK nor flashing DONT WALK phase along both the streets (G(1)=0, A(1)=0; G(2)=0, A(2)=0).

4.2.2 Scenarios with Variable Opposing Pedestrian Volumes

The duration of WALK phase in a reasonable signal plan should only reflect the impact of the critical corresponding pedestrian volume(s).

Cases 14, 18 and 19 are run to verify the GA procedure ability to identify the critical pedestrian movement. As an example, the westbound pedestrian volume, P(3), is varied in this section. P(3) would increase from 200 to 1600 (ped/h) with an increment of 700 (ped/h), while the other volumes remain stable. Table 4.11 lists the detailed settings of hourly vehicle volumes (V) and pedestrian volumes (P) of Cases 14, 18 and 19.

Table 4.11 Setting of Hourly Vehicle (veh/h) and Pedestrian Volumes (ped/h)

In Cases 14, 18, & 19

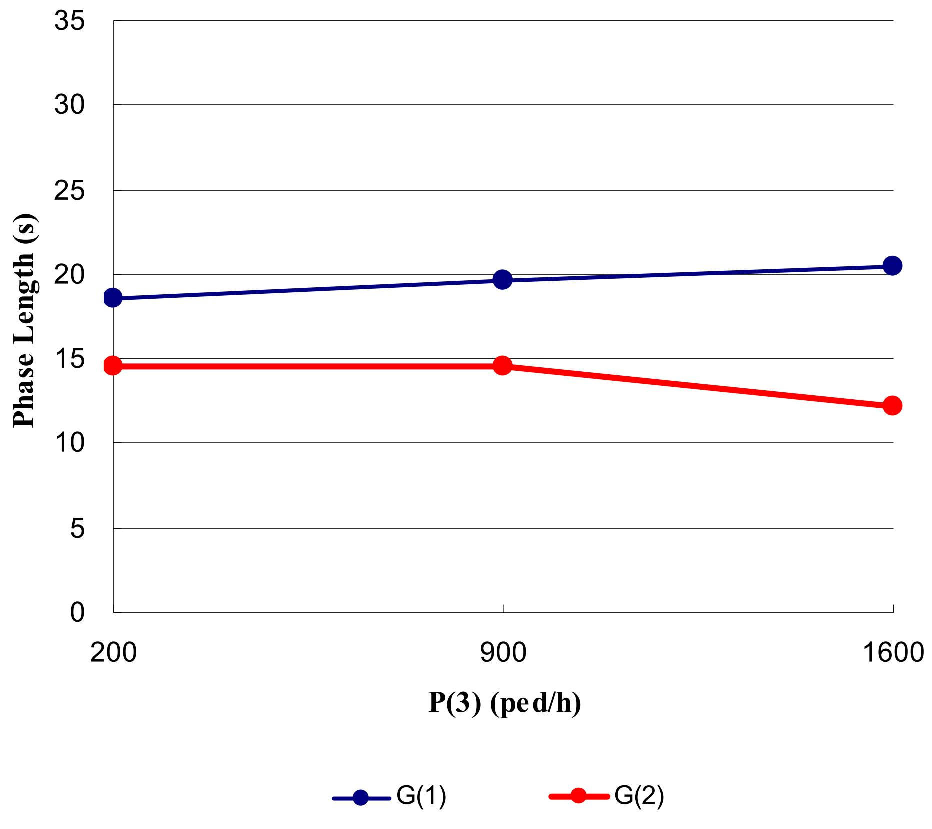
V(1)	**V(2)**	**V(3)**	**V(4)**	**V(5)**	**V(6)**	**P(1)**	**P(2)**
200	400	200	200	400	200	1800	200
V(7)	**V(8)**	**V(9)**	**V(10)**	**V(11)**	**V(12)**	**P(3)**	**P(4)**
200	400	200	200	400	200	[200, 900, 1600]	200

Table 4.12 Optimization Results of Flag, G(1), G(2), and C in Cases 14, 18, & 19

Case		**14**	**18**	**19**
P(3)		***200***	***900***	***1600***
Random Seed #1	***Flag***	0	0	0
	G(1)	23	20	28
	G(2)	17	14	15
	C	114	110	121
Random Seed #2	***Flag***	0	0	0
	G(1)	18	18	17
	G(2)	15	16	11
	C	112	107	102
Random Seed #3	***Flag***	0	0	0
	G(1)	17	18	18
	G(2)	13	11	9
	C	105	106	110
Random Seed #4	***Flag***	0	0	0
	G(1)	18	17	18
	G(2)	14	15	16
	C	106	105	109
Random Seed #5	***Flag***	0	0	0
	G(1)	17	25	21
	G(2)	14	17	10
	C	100	117	104

Note: Except for the variable Flag, all the data are in the unit of seconds.

Figure 4.6 Expected Values of Optimal G(1) and G(2) in Cases 14, 18 & 19



The GA procedure's ability to identify the critical pedestrian movement is effective. Based on the 4 different pedestrian volumes in the intersection, the eastbound pedestrian flow is the critical movement of the WALK phase along the major street in Cases 14, 18 and 19. According to Cases 14, 18 and 19, the duration of the WALK phase along the major street, G(1), remains quite stable. Table 4.12 lists the detailed running results of signal plans by the GA procedure, and Figure 4.6 illustrates the expected values of optimal G(1) and G(2) in Cases 14, 18 and 19.

4.3 Vehicle and Pedestrian Integration Aspect Verification

Verification in Section 4.3 includes tests of scenarios with variable pedestrian, left-trun and through vehicle volumes and scenarios with variable pedestrian and right-turn vehicle volumes.

4.3.1 Scenarios with Variable Pedestrian, Left-Turn and Through Vehicle Volumes

A reasonable signal plan should also be able to reflect the combined impact of the corresponding pedestrian, left-turn and through vehicle volumes. The relevant durations should be raised with the growth of the corresponding pedestrian, left-turn and through vehicle volumes, if the movements are critical.

Furthermore, the type of pedestrian crossing in a reasonable signal plan should reflect the impact of the corresponding pedestrian, left-turn and through vehicle volumes. The type should be changed from two-way crossing to scramble crossing with enormous growth of the corresponding pedestrian, left-turn and through vehicle volumes.

Cases 13 and 20 to 23 are run to verify the combined impact of the corresponding pedestrian, left-turn and through vehicle volumes. As an example, the eastbound pedestrian volume, P(1), eastbound left-turn vehicle volume, V(1), and through vehicle volume, V(2), are all varied in this section. P(1) would increase from 1000 to 4200 (ped/h) with an increment of 800 (ped/h). V(1) would increase from 200 to 1000 (veh/h) with an increment of 200 (veh/h), and V(2) from 400 to 1200 (veh/h) with the same increment, while the other volumes remain stable.

Table 4.13 lists the detailed settings of hourly vehicle volumes (V) and pedestrian volumes (P) of Cases 13 and 20 to 23. In Cases 13 and 20 to 23, based on the 12 different vehicle and the 4 different pedestrian volumes in the intersection, the eastbound left-turn traffic and through traffic are the critical movements of the left-turn and through phases along the major street, and the eastbound pedestrian flow is the critical movement of the WALK phase along the major street.

Table 4.13 Setting of Hourly Vehicle (veh/h) and Pedestrian Volumes (ped/h) In Cases 13 & 20 ~ 23

V(1)	**V(2)**	**V(3)**	**V(4)**	**V(5)**	**V(6)**	**P(1)**	**P(2)**
[200, 400, 600, 800, 1000]	[400, 600, 800, 1000, 1200]	200	200	400	200	[1000, 1800, 2600, 3400, 4200]	200
V(7)	**V(8)**	**V(9)**	**V(10)**	**V(11)**	**V(12)**	**P(3)**	**P(4)**
200	400	200	200	400	200	200	200

Table 4.14 Optimization Results of Flag, G(1), G(2), g(1), g(2), g(4), g(5) and C

In Cases 13 & 20 ~ 23

Case		**13**	**20**	**21**	**22**	**23**
V(1), V(2), P(1)		***200, 400, 1000***	***400, 600, 1800***	***600, 800, 2600***	***800, 1000, 3400***	***1000, 1200, 4200***
Random Seed #1	***Flag***	0	0	0	0	1
	G(1)	18	24	25	29	30
	G(2)	18	16	5	5	0
	C	114	121	114	102	154
	g(1)	16	20	21	17	21
	g(2)	32	40	40	41	41
	g(4)	17	13	10	7	10
	g(5)	31	30	25	19	17
Random Seed #2	***Flag***	0	0	0	0	1
	G(1)	19	19	25	30	31
	G(2)	13	7	5	5	0
	C	112	114	111	107	157
	g(1)	17	19	21	21	21
	g(2)	32	37	37	41	40
	g(4)	15	13	10	7	9
	g(5)	30	27	25	19	21
Random Seed #3	***Flag***	0	0	0	0	1
	G(1)	16	22	26	30	29
	G(2)	17	13	5	5	0
	C	109	115	115	107	149
	g(1)	15	19	21	20	21
	g(2)	31	37	41	41	37
	g(4)	16	13	10	9	8
	g(5)	29	28	25	18	19
Random Seed #4	***Flag***	0	0	0	0	1
	G(1)	19	20	25	30	30
	G(2)	18	5	5	5	0
	C	110	125	114	107	154
	g(1)	15	21	21	21	21
	g(2)	32	40	40	41	39
	g(4)	15	15	10	7	9
	g(5)	30	31	25	19	20

Table 4.14 (cont.)

Random Seed #5	***Flag***	0	0	0	0	1
	G(1)	20	25	26	30	30
	G(2)	15	17	5	5	0
	C	105	118	116	107	153
	g(1)	13	20	21	20	21
	g(2)	32	38	41	41	36
	g(4)	14	13	11	7	9
	g(5)	28	29	25	20	22

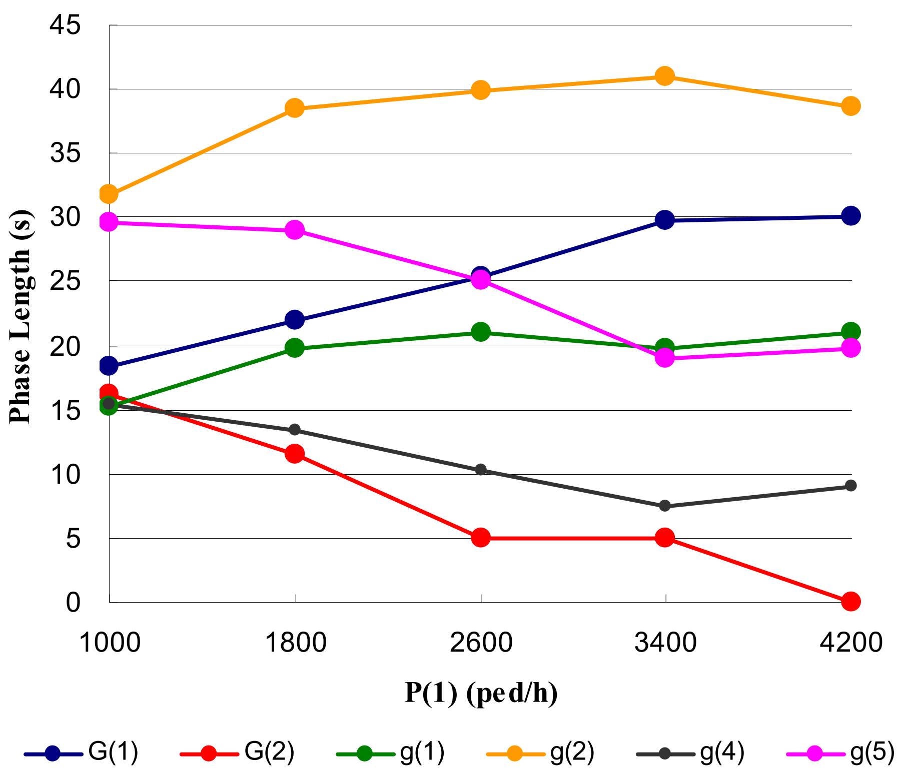
Notes:

1. Except for the variable Flag, all the data are in the unit of seconds.

2. A case listed with gray shade is suggested to apply scramble crossing by the proposed GA optimization procedure

Figure 4.7 Expected Values of

Optimal G(1), G(2), g(1), g(2), g(4), and g(5) in Cases 13 & 20 ~ 23



The vehicle phases selected by the GA procedure are reasonable. The durations of the left-turn and through phases along the major street, g(1) and g(2), increase significantly with V(1)'s increment from 200 to 400 and V(2)'s from 400 to 600. Moreover, according to Cases 21 to 23, after g(1) and g(2) reach their 21-second and 41-second upper limit respectively (refer to Section 3.2.1) with lower V(1) and V(2) (like in Case 20), g(1) and g(2) would remain stable at their maximums even with higher V(1) and V(2). Table 4.14 lists the detailed running results of signal plans by the GA procedure, and Figure 4.7 illustrates the expected values of optimal G(1), G(2), g(1), g(2), g(4), and g(5) in Cases 13 and 20 to 23.

The pedestrian phase selected by the GA procedure is reasonable. According to Cases 13 and 20 to 23, the duration of the WALK phase along the major street, G(1), increases significantly with P(1)'s increment. Furthermore, the type of pedestrian crossing selected by the GA procedure is reasonable. The type of the WALK phase along the major street changes from two-way crossing to scramble crossing after P(1) increases from 3400 to 4200 (ped/h).

4.3.2 Scenarios with Variable Pedestrian and Right-Turn Vehicle Volumes

A reasonable signal plan should also be able to reflect the combined impact of the corresponding pedestrian and right-turn vehicle volumes. The relevant durations should be raised with the growth of the corresponding pedestrian and right-turn vehicle volumes, if the movements are critical. Additionally, since only the permitted right-turn phase is applied in the hypothesized intersection, the impact object of various right-turn volumes on signal plans is the through phase.

Furthermore, the type of pedestrian crossing in a reasonable signal plan should reflect the impact of the corresponding pedestrian and right-turn vehicle volumes. The type should be changed from two-way crossing to scramble crossing with enormous growth of the corresponding pedestrian and right-turn vehicle volumes.

Cases 12 and 24 to 27 are run to verify the combined impact of the corresponding pedestrian and right-turn vehicle volumes. As an example, the eastbound pedestrian volume, P(1), and eastbound right-turn vehicle volume, V(3), are both varied in this section. P(1) would increase from 200 to 2200 (ped/h) with an increment of 500 (ped/h), and V(1) would increase from 200 to 1400 (veh/h) with an increment of 300 (veh/h), while the other volumes remain stable.

Table 4.15 lists the detailed settings of hourly vehicle volumes (V) and pedestrian volumes (P) of Cases 12 and 24 to 27. Based on the 12 different vehicle and the 4 different pedestrian volumes in the intersection, the eastbound through traffic is the critical movement of the through phases along the major street in Cases 12, and the eastbound right-turn traffic is critical in Cases 24 to 27. Meanwhile, the eastbound pedestrian flow is always the critical movement of the WALK phase along the major street in Cases 12 and 24 to 27.

Table 4.15 Setting of Hourly Vehicle (veh/h) and Pedestrian Volumes (ped/h) In Cases 12 & 24 ~ 27

V(1)	**V(2)**	**V(3)**	**V(4)**	**V(5)**	**V(6)**	**P(1)**	**P(2)**
200	400	[200, 500, 800, 1100, 1400]	200	400	200	[200, 700, 1200, 1700, 2200]	200
V(7)	**V(8)**	**V(9)**	**V(10)**	**V(11)**	**V(12)**	**P(3)**	**P(4)**
200	400	200	200	400	200	200	200

Table 4.16 Optimization Results of Flag, G(1), G(2), g(1), g(2), g(4), g(5) and C In Cases 12 & 24 ~ 27

Case		**12**	**24**	**25**	**26**	**27**
V(3), P(1)		***200, 200***	***500, 700***	***800, 1200***	***1100, 1700***	***1400, 2200***
Random Seed #1	***Flag***	0	0	0	1	1
	G(1)	16	9	13	9	12
	G(2)	10	11	14	0	0
	C	100	118	108	132	127
	g(1)	13	15	12	11	10
	g(2)	28	41	41	41	41
	g(4)	15	15	11	12	10
	g(5)	26	29	26	24	19
Random Seed #2	***Flag***	0	0	0	1	1
	G(1)	20	9	13	9	12
	G(2)	10	8	5	0	0
	C	116	116	110	130	129
	g(1)	17	15	12	11	10
	g(2)	34	41	41	41	41
	g(4)	16	13	12	11	11
	g(5)	31	29	27	23	20
Random Seed #3	***Flag***	0	0	0	1	1
	G(1)	19	9	13	9	12
	G(2)	20	17	8	0	0
	C	117	117	105	132	129

Table 4.16 (cont.)

Random Seed #3	***g(1)***	17	15	10	11	9
	g(2)	31	40	41	41	41
	g(4)	17	14	11	11	12
	g(5)	34	30	25	25	20
Random Seed #4	***Flag***	0	0	0	1	1
	G(1)	17	9	13	10	13
	G(2)	18	14	6	0	0
	C	115	118	106	139	134
	g(1)	16	14	10	13	10
	g(2)	33	41	41	41	41
	g(4)	16	15	11	13	11
	g(5)	32	30	26	27	24
Random Seed #5	***Flag***	0	0	0	1	1
	G(1)	18	9	12	9	12
	G(2)	17	19	5	0	0
	C	112	119	102	132	129
	g(1)	15	14	10	11	10
	g(2)	32	41	41	41	41
	g(4)	16	15	10	12	9
	g(5)	31	31	23	24	22

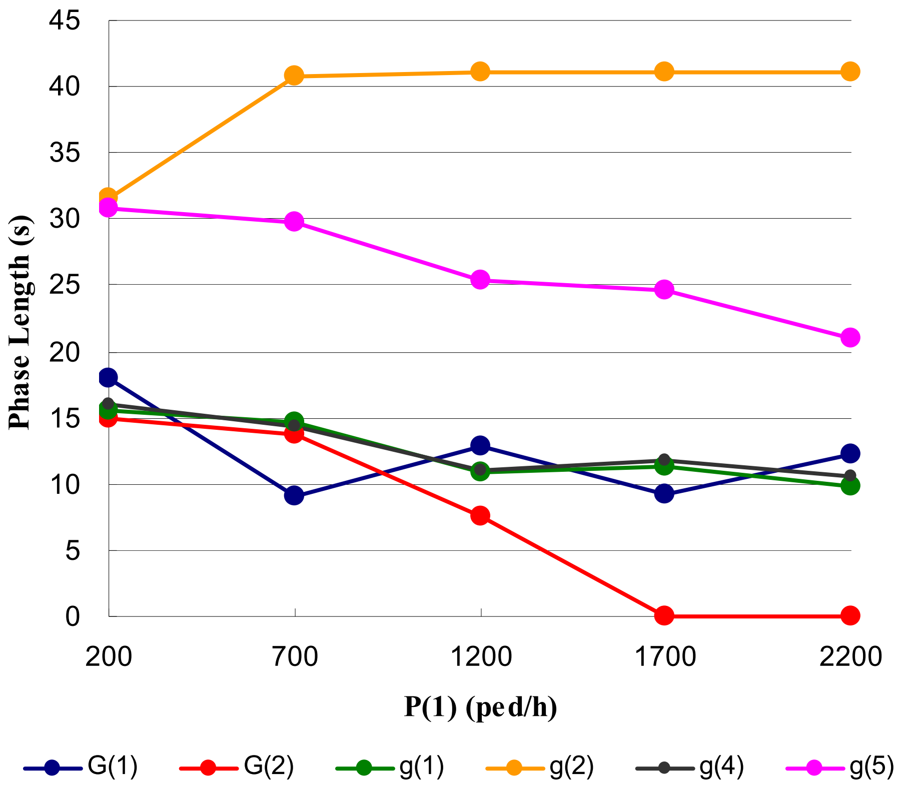
Notes:

1. Except for the variable Flag, all the data are in the unit of seconds.

2. A case listed with gray shade is suggested to apply scramble crossing by the proposed GA optimization procedure

Figure 4.8 Expected Values of

Optimal G(1), G(2), g(1), g(2), g(4), and g(5) in Cases 12 & 24 ~ 27



The vehicle phases selected by the GA procedure are reasonable. The durations of the through phase along the major street, g(1), increase significantly with V(3)'s increment from 200 to 500. Moreover, according to Cases 25 to 27, after g(2) reaches its 41-second upper limit (refer to Section 3.2.1) with lower V(3) (like in Case 24), g(2) would remain stable at its maximum even with higher V(3). Table 4.16 lists the detailed running results of signal plans by the GA procedure, and Figure 4.8 illustrates the expected values of optimal G(1), G(2), g(1), g(2), g(4), and g(5) in Cases 12 and 24 to 27.

The pedestrian phase selected by the GA procedure is reasonable. According to Cases 12 and 24 to 27, the total duration of a WALK phase and a flashing DONT WALK phase along the major street, G(1)+A(1), increases with P(1)'s increment, although G(1) alone does not have an obvious growing tendency with P(1)'s increment. Furthermore, the type of pedestrian crossing selected by the GA procedure is reasonable. The type of the WALK phase along the major street changes from two-way crossing to scramble crossing after P(1) increases from 1200 to 1700 (ped/h), which is a much lower threshold for pedestrian crossing pattern to switch compared with the scenarios tested in Section 4.3.1. This is probably because the GA procedure identifies the major conflict calling for the switch to scramble crossing – the conflict between the pedestrian flow and the right-turn vehicle flow.

4.4 Total User Time Aspect Verification

Section 4.4 verifies reasonableness of total user time from aspects of variable vehicle volumes and variable pedestrian volumes. The total user time results of Cases 4 to 7 and 12 to 17 are employed in the verification.

Reasonable total user time should reflect both impacts of vehicle and pedestrian delay and therefore is influenced by both vehicle and pedestrian volumes. The user time should rise with the growth of either volume. In Cases 4 to 7, only the eastbound through vehicle volume, V(2), is varied (refer to Table 4.3), while only the eastbound pedestrian volume, P(1), is varied in Cases 12 to 17 (refer to Table 4.9).

Table 4.17 Optimization Results of Total User Time in Cases 4 to 7

Case	V (2)	Total Vehicle and Pedestrian User Time ($)				
		Random Seed #1	Random Seed #2	Random Seed #3	Random Seed #4	Random Seed #5
4	***200***	18.37	18.07	17.95	17.94	18.28
5	***400***	20.55	20.17	20.32	20.29	20.21
6	***600***	46.75	46.75	46.81	47.08	46.75
7	***800***	65.69	65.36	65.36	65.36	65.31

Figure 4.9 Expected Values of Optimal Total User Time in Cases 4 to 7

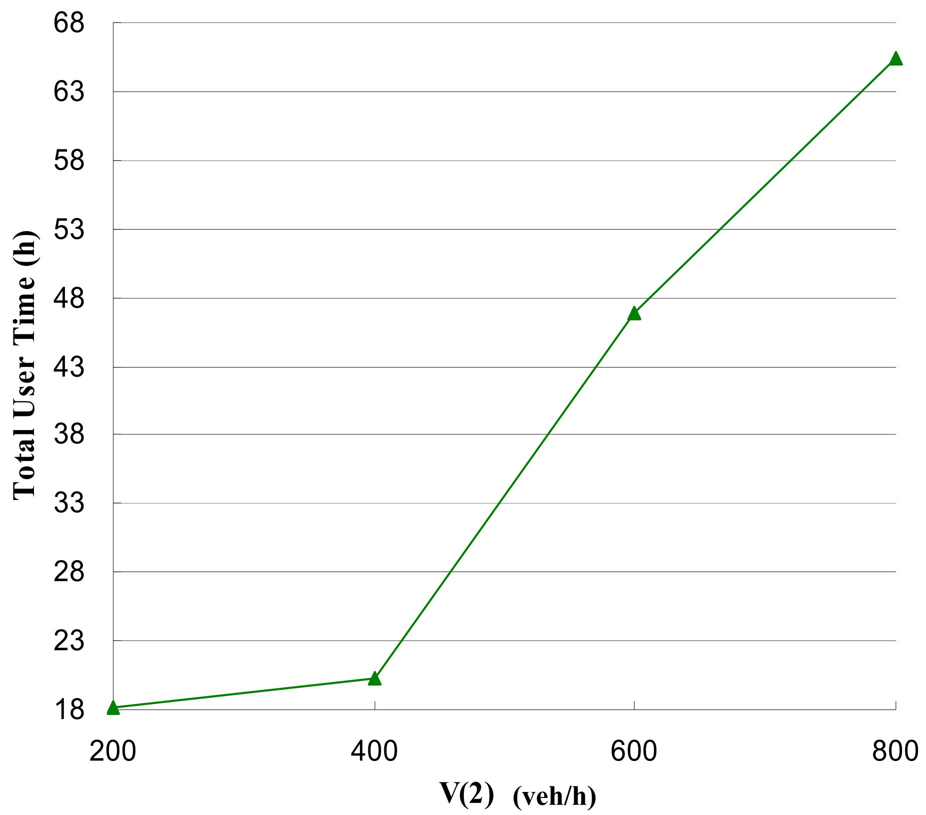
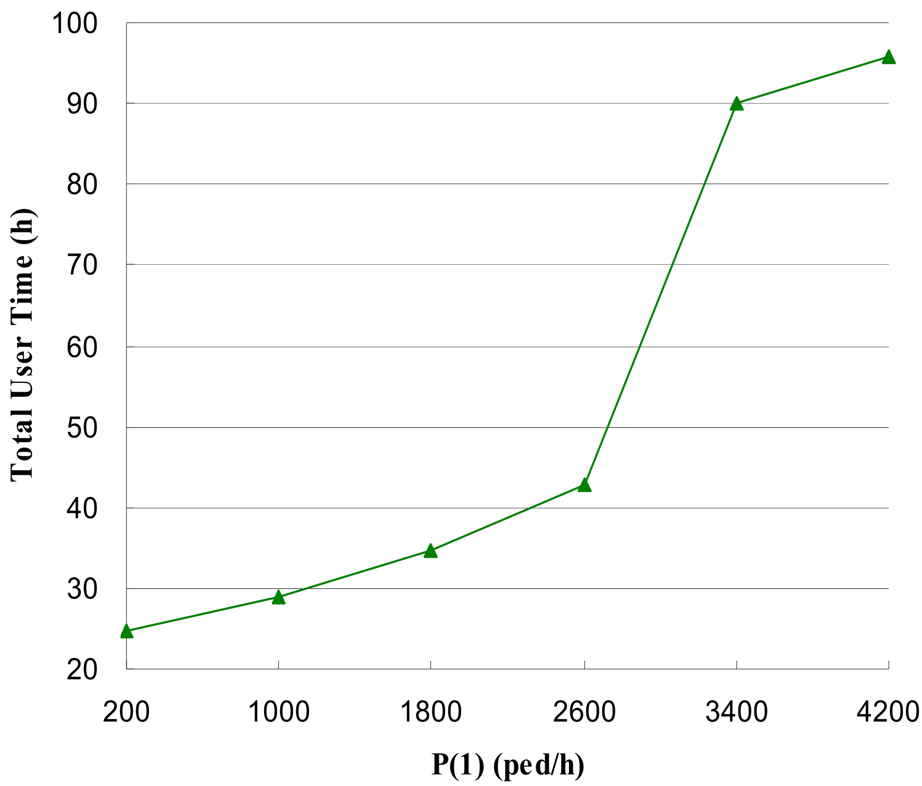


Table 4.18 Optimization Results of Total User Time in Cases 12 to 17

Case	P (1)	Total Vehicle and Pedestrian User Time ($)				
		Random Seed #1	Random Seed #2	Random Seed #3	Random Seed #4	Random Seed #5
12	***200***	24.98	25.11	24.78	24.59	24.51
13	***1000***	29.08	29.24	28.86	28.57	29.04
14	***1800***	34.64	34.89	34.77	34.61	34.54
15	***2600***	42.67	42.69	43.08	42.70	42.78
16	***3400***	56.88	54.79	84.09	84.01	170.68
17	***4200***	95.66	95.71	95.67	95.81	95.80

Figure 4.10 Expected Values of Optimal Total User Time in Cases 12 to 17



Total user time is a reasonable variable to evaluate signal plans in the GA procedure. According to Cases 4 to 7, the user time increases significantly with V(2)'s increment. Table 4.17 lists optimal total user times, and Figure 4.9 illustrates the expected values of optimal total user times in Cases 4 to 7. Moreover, according to Cases 12 to 17, the user time also increases significantly with P(1)'s increment. Table 4.18 lists optimal total user times, and Figure 4.10 illustrates the expected values of optimal total user times in Cases 12 to 17.

Chapter 5

Effectiveness of Genetic Algorithms

Chapter 5 explicates the effectiveness of Genetic Algorithms from three aspects: comparison between theoretical and experimental total delay respectively by HCS and proposed GA procedure, evolution of minimal user in population along generations, and comparison of optimized signal plans by HCS GA function and proposed GA procedure.

5.1 Comparison between Theoretical and Experimental Total Delay

In order to ensure that total delay calculation in the GA procedure is programmed correctly, comparison between theoretical and experimental total delay is made in Section 5.1.

Theoretical total delay (hour) during the analysis period (15 minutes) is calculated by the following equation.

$$Delay_{theoretical} = \frac{1}{3600*4} \sum_{i=1,2,\ldots 12} (avg\_delay(i) * v\_volume\_avg(i))$$

Where avg_delay(i) = lane group i average delay computed by HCS software (sec)

v_volume_avg(i) = number of lane group i vehicles during the analysis period

Detailed setting for the hypothesized HCS intersection is expounded in Chapter 3. If certain parameters are not mentioned in this thesis, they use default values from HCS.

Experimental total delay (hour) during the analysis period is the optimal total user time by the GA procedure divided by the average vehicle occupancy per passenger car (1.22). Since

HCS only covers vehicle delay, Cases 4 to 7, which don't have pedestrian flows in the intersection, are employed to compare with the theoretical total delay by HCS.

The calculation inputs of theoretical and experimental total delay are same, which include vehicle volumes, pedestrian volumes, and initial queues. Table 5.1 lists the detailed theoretical and experimental total delay values of the 5 random seeds in Cases 4 to 7.

Table 5.1 Comparison between the Theoretical Total Delay by HCS and The Experimental Total Delay by the Proposed GA Optimization Procedure

Case		**4**		**5**		**6**		**7**	
V (2)		***200***		***400***		***600***		***800***	
With Initial Queues?		***No***		***No***		***Yes***		***Yes***	
Experimental (Exp) or Theoretical (Theo)		**Theo**	**Exp**	**Theo**	**Exp**	**Theo**	**Exp**	**Theo**	**Exp**
Total Delay (Hour)	**Random Seed #1**	15.07	15.05	16.86	16.84	38.34	38.32	53.98	53.84
	Random Seed #2	14.83	14.82	16.54	16.53	38.34	38.32	53.60	53.57
	Random Seed #3	14.73	14.71	16.67	16.65	38.38	38.37	53.60	53.57
	Random Seed #4	14.73	14.71	16.65	16.63	38.60	38.59	53.60	53.57
	Random Seed #5	15.00	14.98	16.58	16.56	38.34	38.32	53.55	53.53
F		2.885		2.885		2.885		2.885	

According to Table 5.1, all the F-statistics are about the same value, which is 2.885, and smaller than the 0.05 critical value for an F distribution with 1 and 8 degrees of freedom ($F_{0.05}(1,8)=5.318$). Therefore, the difference of the mean experimental total delay and the mean theoretical total delay is not significant at the significance level 0.05. As shown in

Table 5.1, tiny difference between theoretical and experimental values occasionally happens, which is probably caused by different rounding up settings of HCS and the GA procedure during calculation.

Overall, the model performs quite well in the quantitative analysis between theoretical and experimental total delay.

5.2 Evolution of Minimal User Time in Population along Generations

The scenario of Case 4, 5, 26 and 27 with random seed #5 would be used in evolution analysis to verify the effectiveness of the maximum generation setting (50). Each scenario would be run a long enough period, 500 generations, so that the trend of evolution can be observed clearly. The evolution trends of such four scenarios are illustrated in Figures 5.1 and 5.2.

Figure 5.1 Evolution of the Proposed GA Optimization Procedure

From Generation 1 to 500 in Case 4 and 5

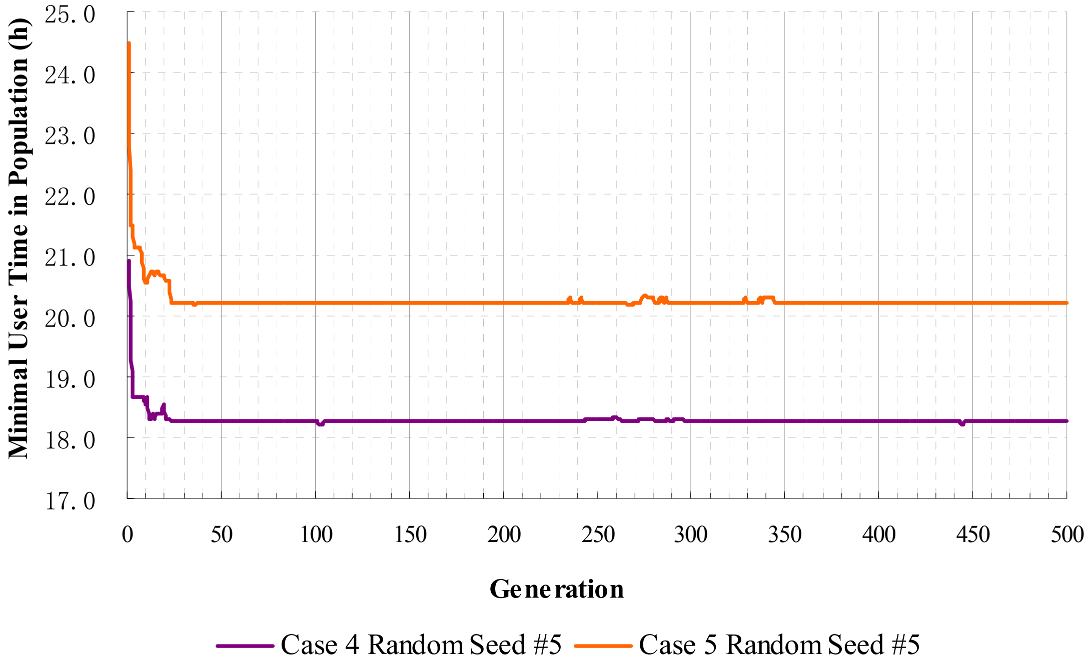
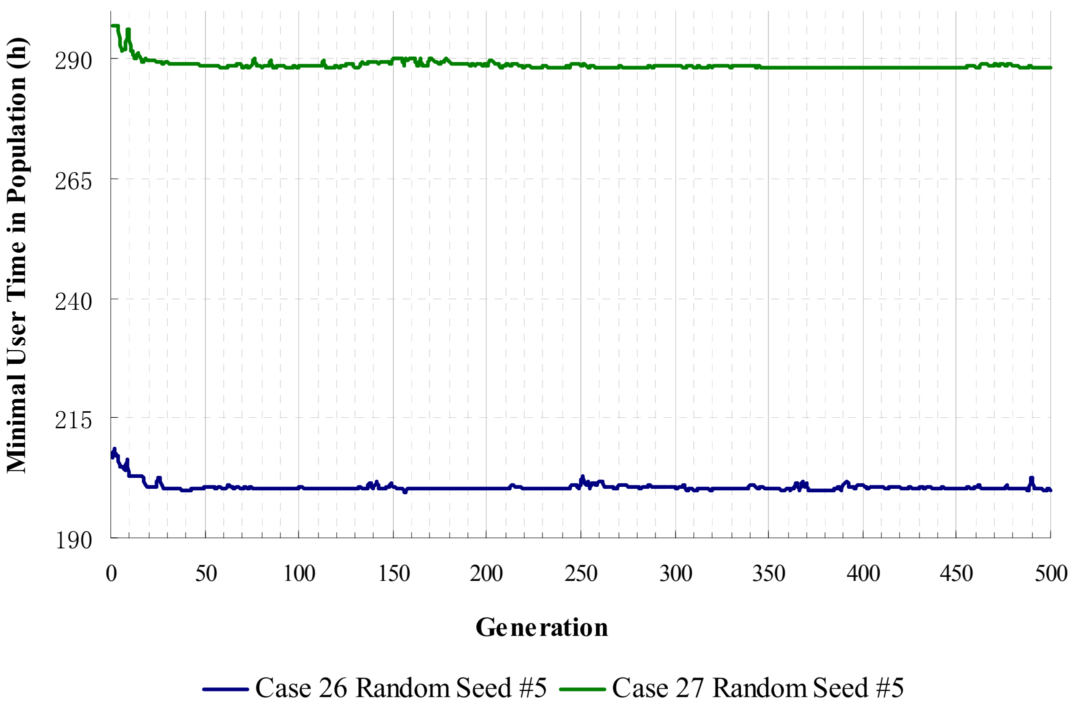


Figure 5.2 Evolution of the Proposed GA Optimization Procedure

From Generation 1 to 500 in Case 26 and 27



As shown in Figures 5.1 and 5.2, the minimal user time in the population drops significantly throughout the first 30 generations. After the 50th generation, the minimal user time becomes reasonably stabilized, although it fluctuates in a small range. Therefore, the maximum generation number (50), which is used in all the tests described in Chapter 4, is effective.

5.3 Comparing between the HCS GA Function and the Proposed GA Optimization Procedure

HCS Software has GA optimization function for signal plan setting as well. Section 5.3 will compare the HCS GA optimization results with the proposed GA procedure results. Since HCS doesn't include pedestrian delay calculation, the comparison would only be discussed from vehicle aspect.

The results of Case 4 and Case 7 with random seed #5 would be used in the comparison analysis as the proposed GA procedure results. Furthermore, their initial queues, vehicle and pedestrian volumes would be the inputs for the HCS GA tests. Other inputs for the HCS GA tests are expounded in Chapter 3. If certain parameters are not mentioned in this thesis, they use default values from HCS.

As for the value of parameters related to the HCS GA function, two separate setting methods are applied in this test, since the critical information about the HCS GA function cannot be accessed, e.g. chromosome structure and GA operators. One uses the same parameters employed by the proposed GA procedure which are explicated in Section 3.2. The other uses the default parameters provided by the HCS GA function. The detailed setting is listed as follows.

- ✧ Cycle length range:

  From 40 to 200 (s) with an increment of 1 (s).

- ✧ Minimum phase times for optimization:

  7 (s) for protected left turn phases and 10 (s) for through and right turn phases

- ✧ Genetic algorithm parameters:

  Crossover probability = 50% (modified), 30% (default)

  Mutation probability = 3.2% (modified, HCS automatically rounds 3.23% up to 3.2%), 4.0% (default)

  Convergence Threshold = 0.01%

  Maximum Number of Generations = 50

  Population Size = 31 (modified), 10 (default)

  Random Number Seed = 6153 (modified), 7781 (default)

  Whether the Elitist Method is applied = no (modified), yes (default)

In addition, the HCS GA function with default critical GA parameters and the proposed GA procedure are both run twice – once without an elitist method, the other with an elitist method.

The initial signal plan setting is the only difference in test input between the proposed GA optimization procedure and the HCS GA function. The GA procedure generates its initial signal plan randomly, while the HCS GA function has to have an initial signal plan imported by users. Thus, each protected left turn phase length is set as 21 seconds, and each through (and permitted right turn) phase is set as 41 seconds. Each yellow change interval length is set as 3 seconds. The length of each red clearance interval after a protected left turn phase is set as 1 second, while that of a through phase is set as 2 seconds.

The detailed optimization results (including signal plan and total delay) of the HCS GA function and the proposed GA procedure are listed in Tables 5.2 and 5.4. (Both the calculation method of total delay is expounded in section 5.1.) Then, HCS is employed to evaluate the results by LOS and average total delay, as shown in Table 5.3 and 5.5.

In the remaining part of this section, in order to simplify the notation, the scenario that the HCS GA function is run by using the modified critical GA parameters and Case 4 (or Case 7) basic setting is represented by Scenario A1 (or C1). If an elitist method is not employed, the scenario that the HCS GA function is run by using the default critical GA parameters and Case 4 (or Case 7) basic setting is represented by Scenario A2 (or C2). Otherwise, it is represented by Scenario A3 (or C3). If an elitist method is not employed, the scenario that the proposed GA procedure is run by using the Case 4 (or Case 7) basic setting is represented by Scenario B1 (or D1). Otherwise, it is represented by Scenario B2 (or D2).

Table 5.2 Signal Plan and Total Delay by the HCS GA Function and the Proposed GA Procedure with Case 4 Basic Setting

Scenario	**A1**	**A2**	**A3**	**B1**	**B2**
Result Source	HCS GA (Case 4 basic setting)			Proposed GA Procedure Case 4, Random Seed #5	
GA parameters	Modified	Default without Elitist	Default with Elitist	Without Elitist	With Elitist
C (sec)	114	97	107	95	113
g(1) (sec)	31.5	13.7	15.4	14	17
g(2) (sec)	15.0	24	28.2	24	29
g(4) (sec)	18.9	15.7	15.3	13	17
g(5) (sec)	30.6	25.6	30.1	26	32
Total Delay (h)	33.0	15.3	14.7	15.0	14.7

Table 5.3 Delay and LOS Evaluation of Scenario A1, A2, A3, B1, and B2 by HCS GA

Scenario	**A1**		**A2**		**A3**		**B1**		**B2**	
	Delay	LOS	Delay	LOS	Delay	LOS	Delay	LOS	Delay	LOS
EBL	37.2	D	90.8	F	88.5	F	77.5	E	79.9	E
EBT	104.5	F	34.6	C	35.9	D	33.3	C	38.6	D
EBR	173.6	F	37.5	D	38.4	D	36.1	D	41.4	D
WBL	37.2	D	90.8	F	88.5	F	77.5	E	79.9	E
WBT	545.5	F	101.9	F	81.0	F	92.8	F	92.8	F
WBR	173.6	F	37.5	D	38.4	D	36.1	D	41.4	D
NBL	64.5	E	60.6	E	91.0	F	99.2	F	79.9	E
NBT	77.5	E	76.6	E	62.1	E	65.3	E	62.8	E
NBR	39.9	D	35.2	D	36.0	D	33.2	C	37.6	D
SBL	64.5	E	60.6	E	91.0	F	99.2	F	79.9	E
SBT	77.5	E	76.6	E	62.1	E	65.3	E	62.8	E
SBR	39.9	D	35.2	D	36.0	D	33.2	C	37.6	D
Intersection Delay	**142.4**	**F**	**66.2**	**E**	**63.6**	**E**	**64.8**	**E**	**63.5**	**E**

Note: All the delay data are in the unit of second per vehicle.

Table 5.4 Signal Plan and Total Delay by the HCS GA Function and the Proposed GA Procedure with Case 7 Basic Setting

Scenario	**C1**	**C2**	**C3**	**D1**	**D2**
Result Source	HCS GA (Case 7 basic setting)			Proposed GA Procedure Case 7, Random Seed #5	
GA parameters	Modified	Default without Elitist	Default with Elitist	Without Elitist	With Elitist
C (sec)	150	174	155	118	118
g(1) (sec)	26.2	28.2	19.3	15	15
g(2) (sec)	74.9	62.3	57.2	41 *(Maximum)*	41 *(Maximum)*
g(4) (sec)	11.2	20.4	20.3	15	15
g(5) (sec)	19.7	45.1	40.2	29	29
Total Delay (h)	86.9	52.9	52.0	53.5	53.5

Table 5.5 Delay and LOS Evaluation of Scenario C1, C2, C3, D1, and D2 by HCS GA

Scenario	**C1**		**C2**		**C3**		**D1**		**D2**	
	Delay	LOS	Delay	LOS	Delay	LOS	Delay	LOS	Delay	LOS
EBL	88.4	F	120.1	F	257.4	F	230.0	F	230.0	F
EBT	136.6	F	362.0	F	332.6	F	367.3	F	367.3	F
EBR	19.3	B	44.0	D	37.7	D	32.2	C	32.2	C
WBL	88.4	F	120.1	F	257.4	F	230.0	F	230.0	F
WBT	25.6	C	63.0	E	53.8	D	51.0	D	51.0	D
WBR	19.3	B	44.0	D	37.7	D	32.2	C	32.2	C
NBL	660.3	F	303.7	F	230.7	F	230.0	F	230.0	F
NBT	730.2	F	197.4	F	190.4	F	203.5	F	203.5	F
NBR	288.7	F	65.8	E	59.5	E	50.3	D	50.3	D
SBL	660.3	F	303.7	F	230.7	F	230.0	F	230.0	F
SBT	730.2	F	197.4	F	190.4	F	203.5	F	203.5	F
SBR	288.7	F	65.8	E	59.5	E	50.3	D	50.3	D
Intersection Delay	**312.8**	**F**	**190.7**	**F**	**187.3**	**F**	**192.9**	**F**	**192.9**	**F**

Note: All the delay data are in the unit of second per vehicle.

(1) Comparison between Scenarios A1 (or C1) and B1 (or D1)

According to the comparison tables, HCS GA optimization favors the direction with the higher traffic flow, but sacrifices the other direction. In Scenario A, north-south direction total hourly volume is 1600 veh/h, while east-west direction total hourly volume is 1400 veh/h. Thus, the LOS of lane groups in the north-south direction is either D or E which is better than lane groups in the east-west direction. The LOS of through and right-turn lane groups in the east-west direction is all F. In Scenario C, east-west direction total hourly volume is 2000 veh/h, while north-south direction total hourly volume is 1600 veh/h. Thus, some of the lane groups in the east-west direction reach LOS C or even B which is much better than those in the north-south direction. The LOS of all lane groups in the north-south direction is F. Therefore, vehicles moving in the direction with lower traffic flow would generally suffer much longer delay. Besides, compared with the proposed GA procedure, HCS GA function favors longer cycle length and usually longer phase length, as shown in Table 5.2.

On the contrary, the proposed GA procedure focuses on minimizing the delay for all the vehicles. Hence, the optimal average delay per vehicle of the proposed procedure in the hypothesized intersection with Case 4 basic setting (64.8 s/veh, LOS E) is 120% less than that of HCS GA (142.4 s/veh, LOS F), and the total delay is also 120% less (15.0 hours versus 33.0 hours). Similarly, the optimal average delay per vehicle of the proposed procedure with Case 7 basic setting (192.9 s/veh) is 62% less than that of HCS GA optimization (312.8 s/veh), and the total delay is also 62% less (53.5 hours versus 86.9 hours).

In addition, the setting of the initial signal plan has a big influence on the optimal result of the HCS GA function, which should not happen if the function works appropriately (as in the remaining part of this section). Thus, it can be concluded that the HCS GA with such modified parameter setting cannot work properly.

(2) Comparison between Scenarios with Modified GA Parameter Setting (A1 and C1) and Scenarios with Default GA Parameter Setting (A2, and C2)

The HCS GA function performs much better with its default critical GA parameters instead of the modified parameters. The optimal delay per vehicle of the HCS GA function with the default critical GA parameters (Case 4: 66.2 s/veh, Case 7: 190.7 s/veh) is much lower than that with the modified parameters (Case 4: 142.4 s/veh, Case 7: 312.8 s/veh), and the total delay with the default parameters is also lower (Case 4: 15.3 h, Case 7: 52.9 h) than that with the modified parameters (Case 4: 33.0 h, Case 7: 86.9 h).

Since the chromosome structure in the HCS GA function is unknown, it is hard to determine suitable critical GA parameters to ensure both the evolution diversity and stability. Thus, the default parameters, which were determine based on the HCS GA chromosome structure, lead to better performance than the modified parameters which do not satisfy the diversity and stability requirement. According to such conclusion, for the future development of the HCS software, it would more user-friendly if either the critical GA parameters cannot be changed by users or critical GA information can be accessed by users. Otherwise, the deficiency discussed in the first comparison part might occur and the results would be degenerated.

(3) Comparison between Scenarios without an Elitist Method (A2, B1, C2, and D1) and Scenarios with an Elitist Method (A3, B2, C3, and D2)

For both the HCS GA function and the proposed GA procedure, compared with scenarios without an elitist method, scenarios with an elitist method can always reach optimal solutions with less or equivalent delay. The optimal delay per vehicle of the HCS GA function with an elitist method (and default critical GA parameters) (Case 4: 63.6 s/veh, Case 7: 187.3 s/veh) is lower than that without an elitist method (Case 4: 66.2 s/veh, Case 7: 190.7 s/veh), and the proposed GA procedure also has the same characteristics between the optimal results with an elitist method (Case 4: 63.5 s/veh, Case 7: 192.9 s/veh) and without an elitist method (Case 4: 64.8 s/veh, Case 7: 192.9 s/veh).

The minimal total delay in scenarios with an elitist method is slightly less than or equivalent to that without an elitist method after 50 generations, because an elitist method prevents losing good solutions that might occur along the generations.

(4) Comparison between Scenarios A2, A3 (or C2, C3) run by the HCS GA function and B1, B2 (or D1, D2) run by the proposed GA procedure

Generally, the optimal signal timings, calculated by the HCS GA function and the proposed GA procedure, have similar optimal signal timing and minor difference in delay per vehicle.

With Case 4 basic setting, the proposed GA procedure performs slightly better than the HCS GA function. The optimal delay per vehicle of the proposed GA procedure (without an elitist method: 64.8 s/veh, with an elitist method: 63.5 s/veh) is slightly less than that of the HCS GA function (without an elitist method: 66.2 s/veh, with an elitist method: 63.6 s/veh).

With Case 7 basic setting, the difference between the results of the proposed GA procedure and the HCS GA function is slightly larger, compared with Case 4. The optimal delay per vehicle of the proposed GA procedure (without an elitist method: 192.9 s/veh, with an elitist method: 192.9 s/veh) is slightly higher than that of the HCS GA function (without an elitist method: 190.7 s/veh, with an elitist method: 187.3 s/veh).

Compared with the results from Case 4 basic setting, the larger proposed-procedure-versus-HCS difference of the results from Case 7 basic setting is caused by the proposed procedure's 41-second upper limit for the through traffic which the HCS GA function do not have. The HCS GA function ranges the east-west direction through phase length around 1 minute. Although such signal timing causes less traffic delay, the cycle length, ranged from 2.5 minutes to 3 minutes, might not be as practical as the 118-second cycle length proposed by the GA procedure.

However, if long cycle lengths are advantageous for the intersection, the upper limit for the through traffic can be removed. For example, as shown in Table 5.6, after the upper limit of through phases is raised up to 72 seconds, the optimal delay per vehicle of the proposed GA procedure (without an elitist method: 187.5 s/veh, with an elitist method: 186.7 s/veh) is slightly less than that of the HCS GA function (without an elitist method: 190.7 s/veh, with an elitist method: 187.3 s/veh).

Table 5.6 Signal Plan and Total Delay by the HCS GA Function and the Proposed GA Procedure with Case 7 Basic Setting after the Through Phase Upper Limit Raised

Scenario	C2	C3	D1	D2
Result Source	HCS GA (Case 7 basic setting)		Proposed GA Procedure Case 7, Best Result of 5 Random Seeds	
GA parameters	Default without Elitist	Default with Elitist	Without Elitist	With Elitist
C (sec)	174	155	162	166
g(1) (sec)	28.2	19.3	21	21
g(2) (sec)	62.3	57.2	62	64
g(4) (sec)	20.4	20.3	21	21
g(5) (sec)	45.1	40.2	40	42
Intersection Delay (s/veh)	**190.7**	**187.3**	**187.5**	**186.7**

As a whole, when there is no pedestrian at the intersection, the signal plans recommended by the proposed GA with an elitist method result in delay values that are lower than or at least equivalent to the delay values from the HCS GA optimized signal plans. Nevertheless, when pedestrian delay is to be considered in signal timing, such a comparison could not be made because the HCS does not consider pedestrian delay, while the proposed GA considers both vehicles and pedestrians.

Additionally, HCS GA optimization is unable to optimize phase types and sequence of initial signal plan, which is similar to the proposed GA procedure. However, HCS GA function takes longer to run than the GA procedure does in Matlab.

Chapter 6

Studies Utilizing the Proposed GA Procedure

As the results of the proposed GA procedure is verified above, its application to several real world problems is possible. Chapter 6 explicates the utilization of the proposed GA optimization procedure to : (1) comparison of a procedure only minimizing vehicle user time and the proposed procedure minimizing both vehicle and pedestrian user time, (2) comparison of pedestrian and vehicle delay for two-way versus scramble crossing, (3) developing contour diagrams and tables as the selection guide for pedestrian crossing patterns and scramble WALK phase length, (4) analyzing the impact of relative time values on optimal signal plans, (5) analyzing the impact of initial queues on optimal signal plans, and (6) discussing advantages of application of the proposed GA procedure.

6.1 Comparison between a Procedure only Minimizing Vehicle User Time and the Proposed Procedure Minimizing both Vehicle and Pedestrian User Time

In order to verify whether the proposed GA procedure improves traffic at an intersection, the proposed procedure is compared with a similar procedure that only considers vehicle delay. In the remaining part of this section, in order to simplify the notation, the proposed procedure minimizing both vehicle and pedestrian user time is represented by Procedure #1, and the procedure only minimizing vehicle user time is represented by Procedure #2. Procedure #2 is developed by the same methodology described in Chapter 3, except that the user time model only employs the second term in the equation (in Section 3.1.1).

In order to make a fair comparison, the inputs (including initial queues, vehicle and pedestrian volumes) are the same for Procedure #1 and #2. Cases 12 and 28 to 31 are run for the comparison analysis. In the hypothesized intersection, the eastbound pedestrian volume, P(1), and the eastbound right-turn volume, V(3), are both varied. P(1) would increase from 100 to 500 (ped/h) with an increment of 100 (ped/h), and V(1) would increase from 100 to 500 (veh/h) with an increment of 100 (veh/h), while the other volumes remain stable. Table 6.1 lists the detailed settings of hourly vehicle volumes (V) and pedestrian volumes (P) of Cases 12 and 28 to 31.

Table 6.1 Setting of Hourly Vehicle (veh/h) and Pedestrian Volumes (ped/h) In Cases 12 & 28 ~ 31

V(1)	**V(2)**	**V(3)**	**V(4)**	**V(5)**	**V(6)**	**P(1)**	**P(2)**
200	400	[100, 200, 300, 400, 500]	200	400	200	[100, 200, 300, 400, 500]	200
V(7)	**V(8)**	**V(9)**	**V(10)**	**V(11)**	**V(12)**	**P(3)**	**P(4)**
200	400	200	200	400	200	200	200

Table 6.2 Comparison between Vehicle User Time and Total Vehicle & Pedestrian User Time Of Procedure #1 and #2 in Cases 12 & 28 ~ 31

Case	V(3), P(1)	Result	Procedure & User Cost Type	Random Seed #1	Random Seed #2	Random Seed #3	Random Seed #4	Random Seed #5
28	*100, 100*	A	*#1 veh*	20.45	20.15	20.45	20.52	20.24
		B	*#1 veh+ped*	23.63	23.8	23.89	23.6	23.63
		C	*#2 veh*	20.24	20.16	20.18	20.16	20.08
		D	*#2 veh+ped*	24.82	24.5	24.75	23.6	24.16
12	*200, 200*	A	*#1 veh*	21.53	20.98	21	20.74	20.82
		B	*#1 veh+ped*	24.99	25.12	24.8	24.6	24.52
		C	*#2 veh*	20.65	20.7	20.78	20.61	20.75
		D	*#2 veh+ped*	25.28	25.88	26.25	25.17	25.48
29	*300, 300*	A	*#1 veh*	22.35	22.61	22.36	22.87	22.83
		B	*#1 veh+ped*	27.47	27.6	27.34	27.45	27.48
		C	*#2 veh*	22.43	22.29	22.4	22.44	22.44
		D	*#2 veh+ped*	27.75	28.01	28.76	27.73	29.2
30	*400, 400*	A	*#1 veh*	28.31	27.96	27.78	27.91	27.92
		B	*#1 veh+ped*	33.76	34.03	33.93	33.81	33.63
		C	*#2 veh*	27.52	27.6	27.67	27.56	27.62
		D	*#2 veh+ped*	34.08	34.21	34.72	34.72	34.4
31	*500, 500*	A	*#1 veh*	36.11	36.7	37.03	36.11	36.51
		B	*#1 veh+ped*	42.6	43.02	43.31	42.56	42.86
		C	*#2 veh*	36.06	36.06	35.92	36.08	36.04
		D	*#2 veh+ped*	43.18	42.86	43.25	43.2	43.01

Note: All the data are in the unit of hours.

Table 6.3 Analytical Summary of Table 6.2

Case	**28**	**12**	**29**	**30**	**31**
Result C - Result A (h)	-0.20	-0.32	-0.20	-0.38	-0.46
Result D - Result B (h)	0.66	0.81	0.82	0.59	0.23
Eq1 (h)**:** **(**Result B)/(Total Ped and Vehicle Volume)	0.0062	0.0062	0.0065	0.0077	0.0093
Eq2 (h)**:** (Result D)/(Total Ped and Vehicle Volume)	0.0064	0.0064	0.0067	0.0078	0.0094
(Eq2 – Eq1)×3600 (s)	0.62	0.62	0.70	0.49	0.18

Compared with Procedure #2, Procedure #1 proposes a signal plan more suitable for both vehicles and pedestrians, although vehicles experience longer delay. Table 6.2 lists and the detailed vehicle user time and total user time of Procedure #1 and #2 in Cases 12 and 28 to 31, and Table 6.3 shows the analytical summary of Table 6.2. According to the Table 6.3, several conclusions can be made.

- ✧ Procedure #1 provides a better signal plan for both vehicles and pedestrians. As shown in Table 6.3, compared with Procedure #2, average total user time saved by Procedure #1 during the analysis period (0.25 hour) is respectively 0.66, 0.81, 0.82, 0.59, and 0.23 hour in Cases 12 and 28 to 31.
- ✧ Most of the time, vehicle user time of Procedure #1 is slightly larger than or close to that of Procedure #2, which means Procedure #1 exchanges extra vehicle delay for lower pedestrian delay. As shown in Table 6.3, compared with Procedure #2, average vehicle delay increased by Procedure #1 during the analysis period (0.25 hour) is respectively 0.20, 0.32, 0.20, 0.38, and 0.46 hour in Cases 12 and 28 to 31.
- ✧ When vehicle volumes are relatively low, the reduction in total user time is larger than the increment in vehicle user time, probably because the pedestrian time value is twice the vehicle time value. When vehicle volumes are relatively high such as in Case 31, the reduction in total user time is not as large as the increment in vehicle user time, because vehicle user time dominates total user time after the average delay multiplies the large volume. However, as shown in Table 6.3, the average user time per person of Procedure #1 during the analysis period (0.25 hour) is still 0.62, 0.62, 0.70, 0.49, and 0.18 second lower than that of Procedure #2 respectively in Cases 12

and 28 to 31, which indicates the objects of the optimization are both pedestrian and vehicle users. Nevertheless, with increment of vehicle and pedestrian volumes, the difference between the two procedures diminishes, plausibly due to limited space for the “trade-off”.

6.2 Comparison of Pedestrian and Vehicle Delay for Two-Way and Scramble Crossing

In this section, the impact of scramble crossing on pedestrian and vehicle delay is discussed. Pedestrian and vehicle delay of two-way and scramble crossing are compared in the same traffic volume and intersection geometric conditions. Eight tests are run with different volumes for this comparison. Each test is replicated by 5 different random seeds whose average is listed in Table 6.4 which shows the detailed total user time, pedestrian and vehicle delay comparison between two-way and scramble crossing.

The volume combinations for the 8 tests are varied based on moderate and high volumes of 3 variables:

- ✧ Moderate and high through vehicle volumes (T = 450 veh/h and 950 veh/h),
- ✧ Moderate and high right-turn vehicle volumes (RT = 450 veh/h and 950 veh/h),
- ✧ Moderate and high pedestrian volumes (Ped = 400 veh/h and 800 veh/h).

These volume combinations will be used in generating contour diagrams in Section 6.3.

Table 6.4 Total User Time, Pedestrian and Vehicle Delay Comparison Between Two-Way and Scramble Crossing

Test No.	**Volumes** (veh/h or ped/h)			**Scramble Crossing**			**Two-Way Crossing**		
	T	Ped	RT	Total User Time (h)	Ped Delay (h)	Vehicle Delay (h)	Total User Time (h)	Ped Delay (h)	Vehicle Delay (h)
1	450	400	450	96.14	6.49	83.16	77.02*	5.26	66.50
2	450	400	950	400.11	6.08	387.94	372.14*	4.83	362.49
3	450	800	450	111.04	12.75	85.54	99.47*	9.67	80.13
4	450	800	950	416.90*	12.06	392.78	433.84	9.04	415.77
5	950	400	450	354.81	6.11	342.60	273.35*	4.80	263.75
6	950	400	950	612.87	5.81	601.25	534.60*	4.71	525.18
7	950	800	450	370.54	12.13	346.29	293.82*	9.04	275.74
8	950	800	950	630.15	11.65	606.85	589.89*	9.00	571.90

Note:

1. Total User Time = Pedestrian Delay ×Relative Time Value + Vehicle Delay

Relative Time Value = 2

2. "" indicates the pedestrian crossing pattern is recommended by the GA procedure.*

As shown in Table 6.4, only in the Test No.4, scramble crossing is recommended by the GA procedure. If two-way crossing is implemented in the intersection, pedestrian delay would decrease, while vehicle delay would increase. Furthermore, in other Tests No. 1 to 3 and 5 to 8, two-way crossing is recommended by the GA procedure. If scramble crossing is implemented in the intersection, both pedestrian and vehicle delay would increase.

Therefore, scramble crossing increases pedestrian delay, because there is only one phase in the cycle that allows pedestrians to cross (the phase is exclusive – not overlapping with any other phases). As for the impact of scramble crossing on vehicle delay, it depends on the volumes of corresponding pedestrian and right-turn vehicle flows. If the volumes are high, scramble crossing would decrease vehicle delay, because of the elimination of the conflict between pedestrian and right-turn vehicle flow that can lead to the capacity reduction of right-turn lane groups. On the other hand, if the corresponding pedestrian and right-turn vehicle volumes are low, scramble crossing would increase vehicle delay, because the extra waiting time from the scramble phases overwhelms the capacity reduction effect on right-turn lane groups.

6.3 The Selection Guide for Pedestrian Crossing Patterns

In this section, the proposed GA procedure is used to generate appropriate pedestrian crossing patterns and scramble WALK phase lengths based on combinations of different right-turn vehicle volumes, through vehicle volumes, and pedestrian volumes. The traffic pattern combinations (Traffic Pattern #1, Table 6.5) have the following characteristics:

- ✧ All four pedestrian volumes (Variable Z) vary with the same amount from 400 to 2000 with an increment of 400 (ped/h).
- ✧ All four right-turn vehicle volumes (Variable X) vary with the same amount from 200 to 1200 with an increment of 250 (veh/h).
- ✧ All four through vehicle volumes (Variable Y) vary with the same amount from 200 to 1200 with an increment of 250 (veh/h).
- ✧ All four left-turn vehicle volumes remain at 200 (veh/h).

Table 6.5 Hourly Vehicle (veh/h) and Pedestrian Volumes (ped/h) of Traffic Patten #1

V(1)	**V(2)**	**V(3)**	**V(4)**	**V(5)**	**V(6)**	**P(1)**	**P(2)**
200	Y	X	200	Y	X	Z	Z
V(7)	**V(8)**	**V(9)**	**V(10)**	**V(11)**	**V(12)**	**P(3)**	**P(4)**
200	Y	X	200	Y	X	Z	Z

Table 6.6 Scramble WALK Phase Length

Suggested by Proposed GA Procedure in Guide Generation Tests

Y	X	Z	Phase Length	Y	X	Z	Phase Length	Y	X	Z	Phase Length
200	200	400	T	700	200	400	T	1200	200	400	T
200	200	800	T	700	200	800	T	1200	200	800	T
200	200	1200	T	700	200	1200	T	1200	200	1200	T
200	200	1600	T	700	200	1600	T	1200	200	1600	T
200	200	2000	8	700	200	2000	T	1200	200	2000	T
200	450	400	T	700	450	400	T	1200	450	400	T
200	450	800	6	700	450	800	T	1200	450	800	T
200	450	1200	8	700	450	1200	T	1200	450	1200	T
200	450	1600	10	700	450	1600	T	1200	450	1600	T
200	450	2000	12	700	450	2000	T	1200	450	2000	T
200	700	400	T	700	700	400	T	1200	700	400	T
200	700	800	6	700	700	800	T	1200	700	800	T
200	700	1200	8	700	700	1200	T	1200	700	1200	T
200	700	1600	10	700	700	1600	10	1200	700	1600	T
200	700	2000	13	700	700	2000	13	1200	700	2000	T
200	950	400	T	700	950	400	T	1200	950	400	T
200	950	800	6	700	950	800	T	1200	950	800	T
200	950	1200	7	700	950	1200	8	1200	950	1200	T
200	950	1600	10	700	950	1600	10	1200	950	1600	10
200	950	2000	13	700	950	2000	13	1200	950	2000	13
200	1200	400	T	700	1200	400	T	1200	1200	400	T
200	1200	800	6	700	1200	800	6	1200	1200	800	T
200	1200	1200	7	700	1200	1200	7	1200	1200	1200	8
200	1200	1600	10	700	1200	1600	10	1200	1200	1600	10
200	1200	2000	13	700	1200	2000	13	1200	1200	2000	13

Table 6.6 (cont.)

450	200	400	T	950	200	400	T	
450	200	800	T	950	200	800	T	
450	200	1200	T	950	200	1200	T	
450	200	1600	T	950	200	1600	T	
450	200	2000	T	950	200	2000	T	
450	450	400	T	950	450	400	T	
450	450	800	T	950	450	800	T	
450	450	1200	T	950	450	1200	T	
450	450	1600	10	950	450	1600	T	
450	450	2000	13	950	450	2000	T	
450	700	400	T	950	700	400	T	
450	700	800	T	950	700	800	T	
450	700	1200	7	950	700	1200	T	
450	700	1600	10	950	700	1600	T	
450	700	2000	13	950	700	2000	13	
450	950	400	T	950	950	400	T	
450	950	800	6	950	950	800	T	
450	950	1200	7	950	950	1200	8	
450	950	1600	10	950	950	1600	12	
450	950	2000	13	950	950	2000	13	
450	1200	400	T	950	1200	400	T	
450	1200	800	6	950	1200	800	T	
450	1200	1200	7	950	1200	1200	7	
450	1200	1600	10	950	1200	1600	10	
450	1200	2000	13	950	1200	2000	12	

Notes:

1. All the vehicle volumes (Xs and Ys) are in the unit of veh/h.

All the pedestrian volumes (Zs) are in the unit of ped/h.

All the scramble WALK Phase lengths are in the unit of seconds.

2. "T" for the scramble WALK Phase length indicates two-way crossing is suggested by the proposed GA procedure.

Table 6.6 is the running result of the proposed GA procedure for the 125 different combinations of volumes. The table shows which pedestrian crossing pattern is more appropriate and how the pedestrian scramble WALK phase length changes (if the scramble crossing is recommended). The scramble WALK phase length in each volume combination is acquired from the median value of the minimal user times by 5 different random seeds, and is rounded up to the closest integer.

Figures 6.1, 6.2, 6.3, 6.4, and 6.5 are the contour diagrams for the scramble WALK phase lengths listed in Table 6.6. The contour diagrams are all based on a scale: 0 and 6 to 14 with an increment of 1 second. The green areas in the contour diagrams indicate that two-way crossing is suggested by the proposed GA procedure.

Figure 6.1 Contour Diagram of Scramble WALK Phase Lengths (Sec) when Y = 200 (veh/h)

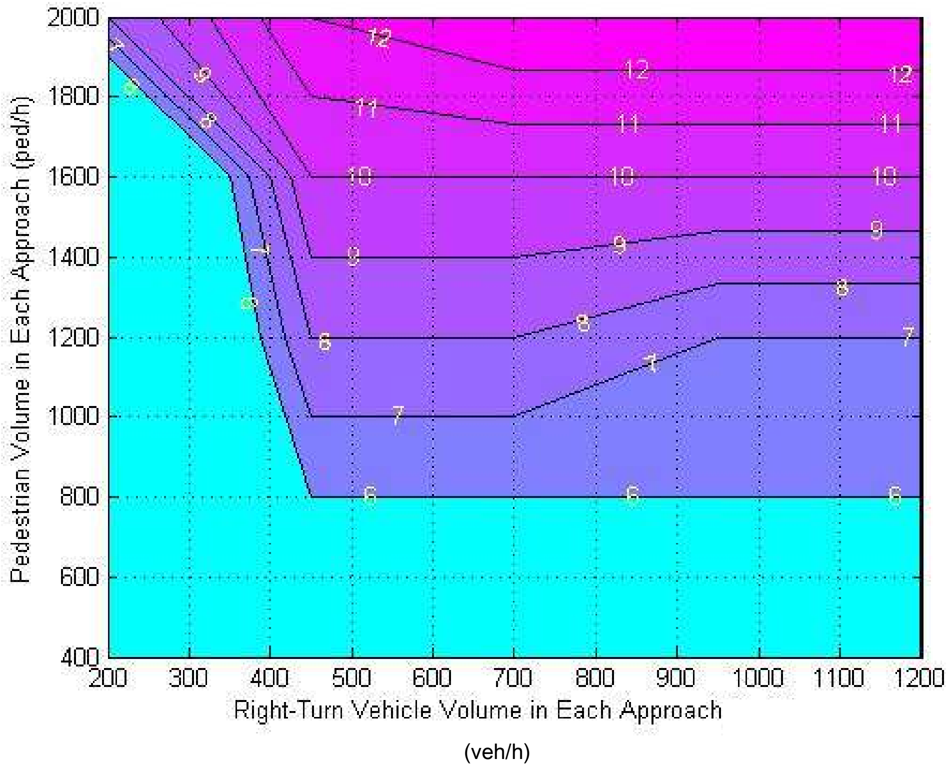


Figure 6.2 Contour Diagram of Scramble WALK Phase Lengths (Sec) when Y = 450 (veh/h)

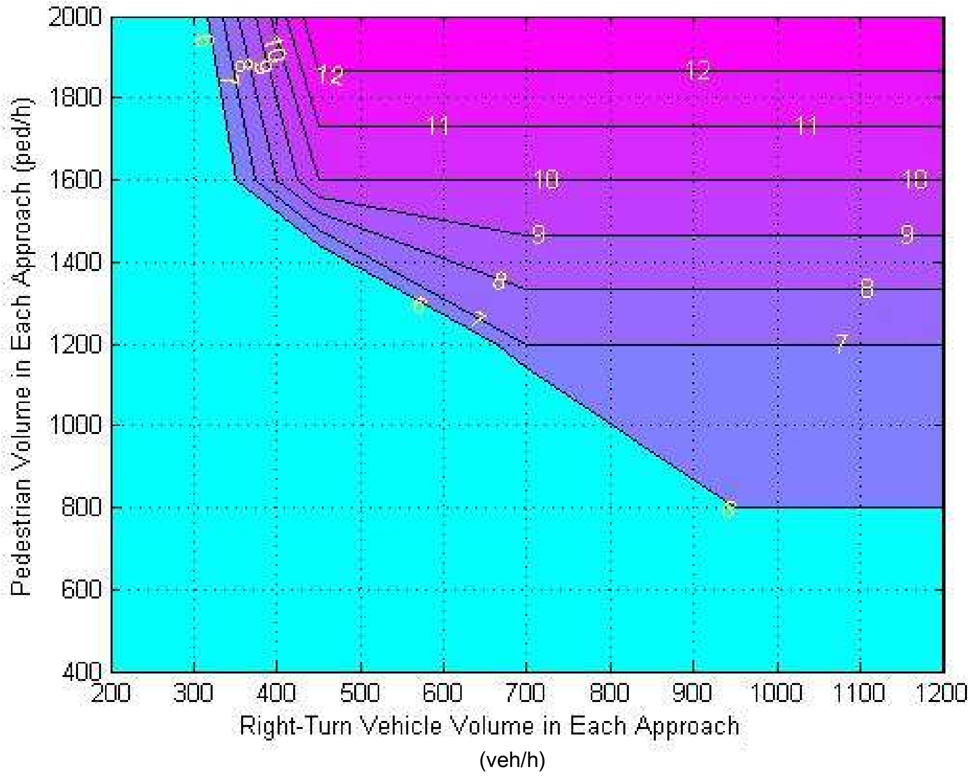


Figure 6.3 Contour Diagram of Scramble WALK Phase Lengths (Sec) when Y = 700 (veh/h)

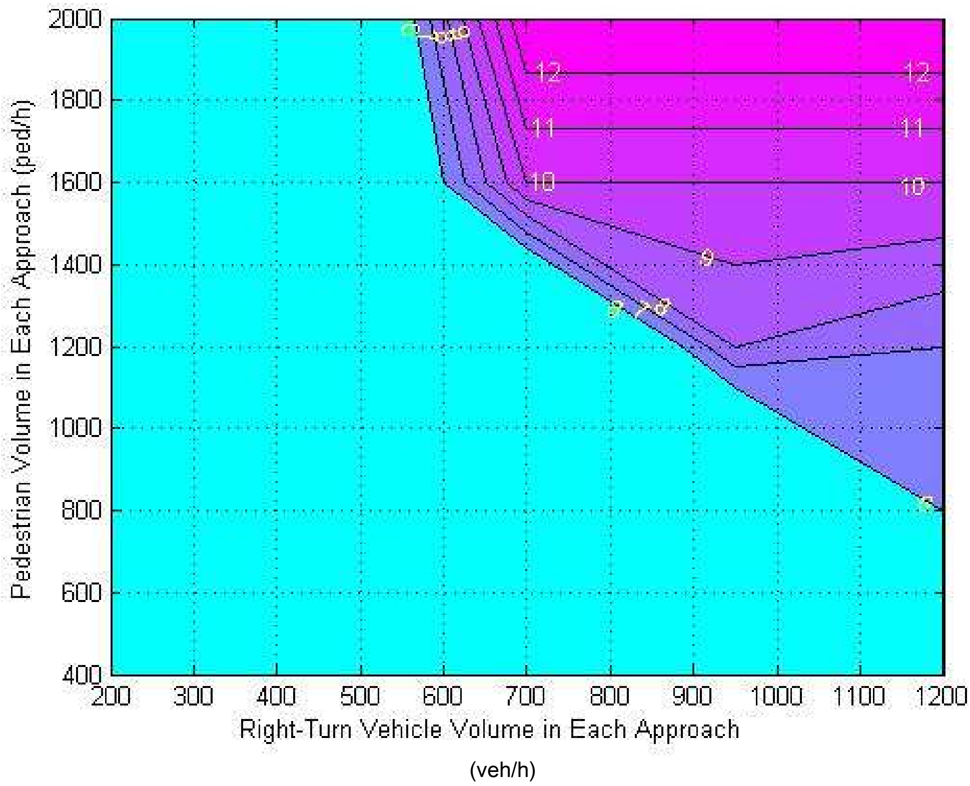


Figure 6.4 Contour Diagram of Scramble WALK Phase Lengths (Sec) when Y = 950 (veh/h)

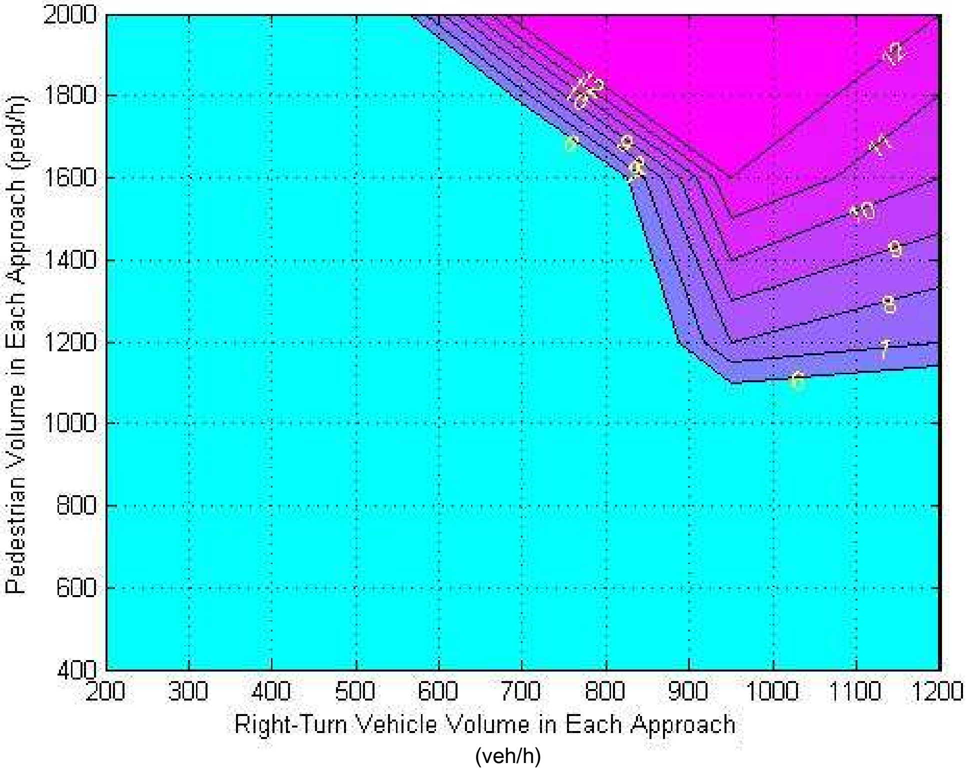
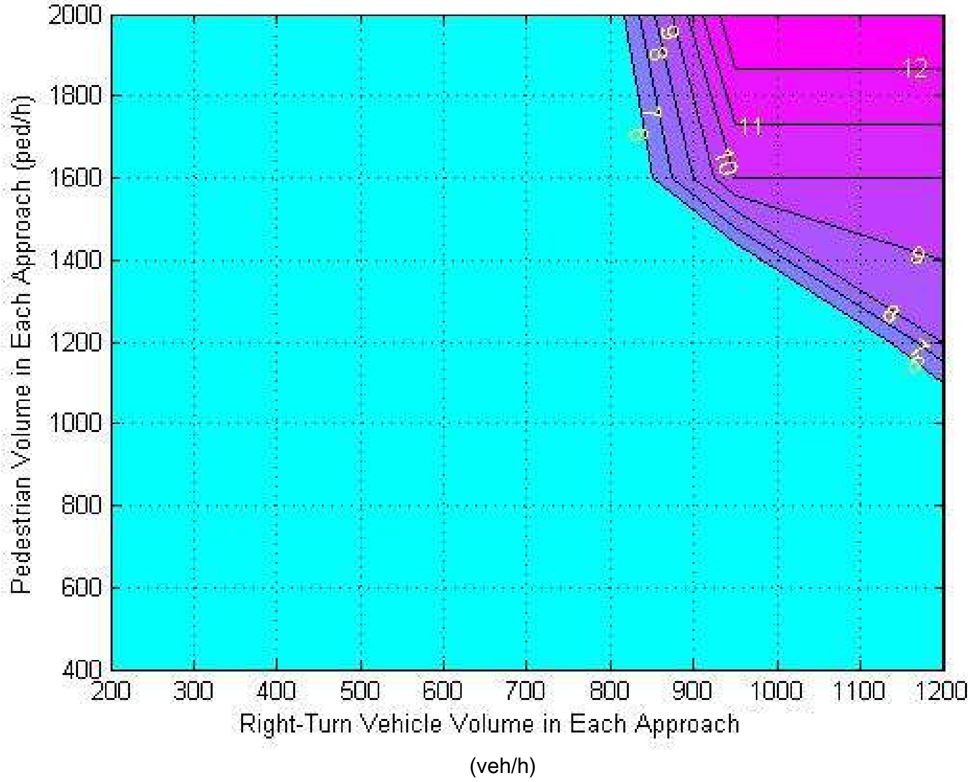


Figure 6.5 Contour Diagram of Scramble WALK Phase Lengths (Sec) when Y = 1200 (veh/h)



As shown in Figures 6.1, 6.2, 6.3, 6.4, and 6.5, the proposed GA procedure selects suitable scramble WALK phase lengths by considering both pedestrian and vehicle delay. With an increase in pedestrian volume, right-turn vehicle volume, or both, the pedestrian crossing pattern switches from two-way crossing to scramble crossing. If the vehicle volumes are fixed, the scramble WALK phase length goes up with the growth of the pedestrian volumes. If the pedestrian and through vehicle volumes are fixed, the scramble WALK phase length remains relatively stable with the growth of the right-turn vehicle volumes, so that the right-turn vehicles would not experience longer waiting time.

Furthermore, according to the figures, with the increase in through vehicle volumes, the scramble WALK phase length decreases and the threshold for the pedestrian crossing pattern (to switch from two-way crossing to scramble crossing) shifts to higher values. This is because the total vehicle delay would increase with higher through traffic and overwhelm the request for scramble crossing due to the increased pedestrian delay. Thus, the GA procedure raises the threshold for scramble crossing. It is anticipated that the impact of left-turn vehicle volumes on optimal signal plans would be similar to that of through volumes.

Therefore, when a traffic engineer is considering the appropriate pedestrian crossing pattern for an intersection, not only pedestrian volumes and right-turn vehicle volumes need to be taken into account, but also through (and left-turn) vehicle volumes.

In the remaining part of this section, in order for the proposed procedure to show its flexibility to solve signal optimization problems, two more tests are run to develop guide tables for another traffic pattern (Traffic Patten #2) and another intersection geometric layout

(Intersection #2).

Traffic Patten #2 describes a situation that could occur in a medium traffic area with a facility that attracts a large number of pedestrians, e.g. a movie theater. Traffic Patten #2 has a variable eastbound pedestrian volume (Variable Y), a variable right-turn vehicle volume (Variable X), and the other volumes remain stable. Variable X and Y vary in a reasonable range with an increment of 100 (veh/h or ped/h). Tables 6.7 lists the details of hourly vehicle volumes (V) and pedestrian volumes (P) of Traffic Patten #2.

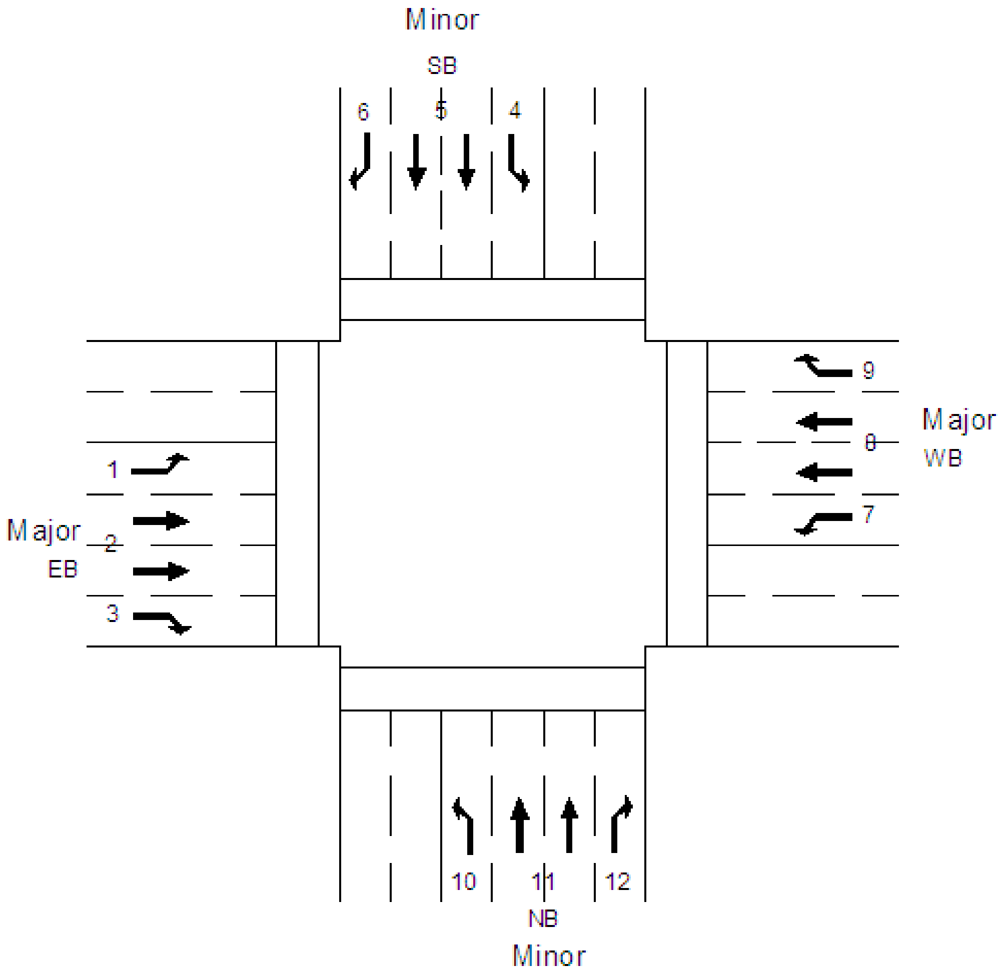
The layout of Intersection #2 is illustrated in Figures 6.6. There are two receiving lanes, two through lanes, one exclusive left-turn lane, and one exclusive right-turn lane in each approach of the intersection. Intersection #2 would employ Traffic Pattern #2 in the test.

In order to simplify the notation, the scenarios with Traffic Pattern #2 in Intersection #1 (Figure 3.2) and Intersection #2 (Figure 6.6) are respectively represented by Scenarios 1 and 2.

Table 6.7 Hourly Vehicle (veh/h) and Pedestrian Volumes (ped/h) of Traffic Patten #2

V(1)	**V(2)**	**V(3)**	**V(4)**	**V(5)**	**V(6)**	**P(1)**	**P(2)**
200	400	Variable X	200	400	200	Variable Y	200
V(7)	**V(8)**	**V(9)**	**V(10)**	**V(11)**	**V(12)**	**P(3)**	**P(4)**
200	400	200	200	400	200	200	200

Figure 6.6 The Diagram of the Hypothesized Intersection #2



Tables 6.8 and 6.9 are the guide tables for Scenarios 1 and 2 respectively. The tables show which pedestrian crossing pattern is more appropriate and how the pedestrian scramble WALK phase length changes (if the scramble crossing is recommended). The scramble WALK phase length in the tables is acquired from the median value of the minimal user times by 5 different random seeds, and is rounded up to the closest integer.

In Tables 6.8 and 6.9, there are three background colors – white, darker green, and lighter green. White background indicates that two-way crossing is suggested by the GA procedure in all the 5 random seed runs, and therefore two-way crossing is more appropriate in the situation. Darker green background indicates that scramble crossing is suggested by the GA procedure in 4 or 5 runs out of the 5 random seed runs, and therefore scramble crossing is more appropriate in the situation. Lighter green indicates that scramble crossing is suggested by the GA procedure in 1, 2, or 3 runs out of the 5 random seed runs. Such "lighter green" situations rarely occur in the previous contour diagram analysis, because the following two tests employ smaller intervals (100 veh/h or 100 ped/h) instead of larger intervals in the previous analysis (250 veh/h or 400 ped/h), which enables Tables 6.8 and 6.9 to have better accuracy.

In the "lighter green" situations, it depends on a traffic engineer's personal judgment to decide which pedestrian crossing pattern is more appropriate. The decision would be mainly influenced by how the engineer evaluates the pedestrian time value compared with the passenger car time value, which can be interpreted as the K value. Section 6.4 explains the impact of different relative time values (K) on selecting an appropriate pedestrian crossing pattern.

Table 6.8 Scramble WALK Phase Length in Scenario 1 Suggested by Proposed GA Procedure

V(3) / P(1)	700	800	900	1000
1400	T	T	T	7
1500	T	T	8	8
1600	T	T	9	9
1700	T	10	10	10
1800	T	11	10	10
1900	12	11	11	11
2000	12	12	12	12
2100	14	13	12	12
2200	14	14	13	13

Notes: 1. All the data are in the unit of seconds.

2. "T" indicates two-way crossing is suggested by the proposed GA procedure.

Table 6.9 Scramble WALK Phase Length in Scenario 2 Suggested by Proposed GA Procedure

V(3) / P(1)	700	800	900	1000
1000	T	T	T	T
1100	T	T	T	5
1200	T	T	5	5
1300	T	6	6	6
1400	T	7	7	6
1500	8	8	8	7
1600	9	9	8	8
1700	10	9	9	9

Notes: 1. All the data are in the unit of seconds.

2. "T" indicates two-way crossing is suggested by the proposed GA procedure.

As shown in Tables 6.8 and 6.9, the proposed GA procedure selects suitable scramble WALK phase lengths by considering both pedestrian and vehicle delay. With the increment of the eastbound pedestrian volume or right-turn vehicle volume, the pedestrian crossing pattern switches from two-way crossing to scramble crossing. If all the vehicle and pedestrian volumes (except the eastbound pedestrian volume) are fixed, the scramble WALK phase length goes up with the growth of the eastbound pedestrian volume. If the pedestrian and vehicle volumes (except the eastbound right-turn vehicle volume) are fixed, the scramble WALK phase length remains relatively stable with the growth of the eastbound right-turn vehicle volume, so that the right-turn vehicles would not experience longer waiting time.

Furthermore, according to Figure 6.2 (with Traffic Pattern #1) and Table 6.8 (with Traffic Pattern #2), the threshold for the pedestrian crossing pattern (to switch from two-way crossing to scramble crossing) of Traffic Pattern #2 is much higher that of Traffic Pattern #1 (e.g. with 700 ped/h, Pattern #2 2100 veh/h versus Pattern #1 1150 veh/h). It is because Traffic Pattern #1 increases the pedestrian and right-turn vehicle volumes of four approaches at the same time, while Traffic Pattern #2 increases only the eastbound pedestrian and right-turn vehicle volumes. Thus, the GA procedure raises the scramble crossing threshold for Traffic Patten #2.

Moreover, by comparing Table 6.8 and Table 6.9, it takes approximately 400 (ped/h) less pedestrian or 200 (veh/h) less vehicle volumes for the pedestrian crossing pattern to switch from two-way crossing to scramble crossing. It can be explained that, with one more through lane in each approach, pedestrians would experience longer delay due to the longer crosswalk length. Thus, the GA procedure lowers the threshold for scramble crossing.

Except for the relative time value (K), a traffic engineer should realize that the average vehicle occupancy per passenger car (n_v) might also need some adjustments, when applying the optimization procedure to an intersection in the real world. The default value (n_v = 1.22), which are quoted based on the research by Bhattacharya and Virkler (2005), might not be appropriate for the intersection. The adjustments could refer to on-site surveys or other reference sources.

Additionally, the model can provide a more intuitive way to present the result: using dollars instead of hours as the unit. The conversion can be simply realized by multiplying the result (total user time) by passenger car time value. According to Tables 5-1 and 5-2 in *Manual on Uniform Traffic Control Devices for Streets and Highways* (AASHTO, 2003), the time value of person traveling locally in an automobile is 50% of his or her wage rate, and the average wage of all employees is 18.56 per hour in 2000 dollars. Therefore, the passenger car time value is 9.28 per hour in 2000 dollars, which is 11.54 per hour in 2010 dollars calculated by the NASA inflation calculator.

Although no numerical standard is established to determine suitable pedestrian crossing pattern in this thesis, the model supported by GA is helpful to realize the same purpose of the standard. It is hard to generate a general numerical standard to choose suitable pedestrian crossing pattern and scramble WALK phase length, because the choice is influenced by so many different factors such as vehicle volumes of 12 movements, pedestrian volumes of 4 movements, initial queues of 12 movements, and the geometric layout of the intersection. Nevertheless, the proposed GA procedure and guide tables can assist traffic engineers to reach suitable solutions.

With such guide tables, it would be much easier and quicker for a traffic engineer to decide suitable pedestrian crossing patterns and scramble WALK phase lengths in intersections with different traffic patterns. However, it should be noted that each guide table is developed for each unique situation with specific traffic pattern and intersection geometric layout. Therefore, if an engineer wants to use a guide table to solve an intersection signal timing problem which has different traffic pattern or geometric layout, the proposed GA procedure should be employed first to generate the table.

6.4 Impact of Relative Time Values

In Section 6.4, tests are run to explore the impact of relative time value (K) on optimal signal plans. Relative time value (K) would increase from 0 to 3 (K = 0, 1, 1.22, 2, and 3). The K range can refer to Section 3.1.1. The proposed GA procedure is used to generate appropriate pedestrian crossing patterns and scramble WALK phase lengths based on combinations of different right-turn vehicle volumes and pedestrian volumes. The traffic pattern combinations are based on the traffic characteristics shown in Table 6.5 with the following setting of Variable X, Y, and Z:

- ✧ All four pedestrian volumes (Variable Z) vary with the same amount from 400 to 2000 with an increment of 400 (ped/h).
- ✧ All four right-turn vehicle volumes (Variable X) vary with the same amount from 200 to 1200 with an increment of 250 (veh/h).
- ✧ All four through vehicle volumes (Variable Y) remain at 700 (veh/h).

Table 6.10 is the running result of the proposed GA procedure for the 125 different combinations of volumes under 5 different relative time values. The table shows which pedestrian crossing pattern is more appropriate and how the pedestrian scramble WALK phase length changes (if the scramble crossing is recommended). The scramble WALK phase length in each volume combination is acquired from the median value of the minimal user times by 5 different random seeds, and is rounded up to the closest integer.

Table 6.10 Scramble WALK Phase Length

Suggested by Proposed GA Procedure in Relative Time Value Impact Analysis Tests

K	X	Z	Phase Length	K	X	Z	Phase Length	K	X	Z	Phase Length
0	200	800	T	1.22	200	800	T	3	200	800	T
0	200	1200	T	1.22	200	1200	T	3	200	1200	T
0	200	1600	T	1.22	200	1600	T	3	200	1600	T
0	200	2000	T	1.22	200	2000	T	3	200	2000	T
0	450	400	T	1.22	450	400	T	3	450	400	T
0	450	800	T	1.22	450	800	T	3	450	800	T
0	450	1200	T	1.22	450	1200	T	3	450	1200	T
0	450	1600	T	1.22	450	1600	T	3	450	1600	T
0	450	2000	13	1.22	450	2000	T	3	450	2000	T
0	700	400	T	1.22	700	400	T	3	700	400	T
0	700	800	T	1.22	700	800	T	3	700	800	T
0	700	1200	8	1.22	700	1200	7	3	700	1200	T
0	700	1600	10	1.22	700	1600	10	3	700	1600	10
0	700	2000	13	1.22	700	2000	13	3	700	2000	13
0	950	400	T	1.22	950	400	T	3	950	400	T
0	950	800	T	1.22	950	800	T	3	950	800	T
0	950	1200	8	1.22	950	1200	7	3	950	1200	7
0	950	1600	10	1.22	950	1600	10	3	950	1600	10
0	950	2000	13	1.22	950	2000	13	3	950	2000	12
0	1200	400	T	1.22	1200	400	T	3	1200	400	T
0	1200	800	6	1.22	1200	800	6	3	1200	800	6
0	1200	1200	7	1.22	1200	1200	7	3	1200	1200	7
0	1200	1600	10	1.22	1200	1600	10	3	1200	1600	10
0	1200	2000	13	1.22	1200	2000	12	3	1200	2000	13
1	200	400	T	2	200	400	T				
1	200	800	T	2	200	800	T				
1	200	1200	T	2	200	1200	T				
1	200	1600	T	2	200	1600	T				
1	200	2000	T	2	200	2000	T				
1	450	400	T	2	450	400	T				
1	450	800	T	2	450	800	T				
1	450	1200	T	2	450	1200	T				
1	450	1600	T	2	450	1600	T				
1	450	2000	14	2	450	2000	14				
1	700	400	T	2	700	400	T				

Table 6.10 (cont.)

1	700	800	T	2	700	800	T	
1	700	1200	7	2	700	1200	7	
1	700	1600	10	2	700	1600	10	
1	700	2000	13	2	700	2000	13	
1	950	400	T	2	950	400	T	
1	950	800	T	2	950	800	T	
1	950	1200	8	2	950	1200	8	
1	950	1600	10	2	950	1600	10	
1	950	2000	13	2	950	2000	13	
1	1200	400	T	2	1200	400	T	
1	1200	800	6	2	1200	800	6	
1	1200	1200	7	2	1200	1200	7	
1	1200	1600	10	2	1200	1600	10	
1	1200	2000	12	2	1200	2000	13	

Notes:

1. *All the vehicle volumes (Xs and Ys) are in the unit of veh/h.*

   All the pedestrian volumes (Zs) are in the unit of ped/h.

   All the scramble WALK Phase lengths are in the unit of seconds.

2. *"T" for the scramble WALK Phase length indicates two-way crossing is suggested by the proposed GA procedure.*

Figures 6.7, 6.8, 6.9, 6.3, and 6.10 are the contour diagrams of scramble WALK phase lengths in Table 6.10 when relative time value (K) equals 0, 1, 1.22, 2, and 3 respectively. The contour diagrams are all based on a scale: 0 and 6 to 14 with an increment of 1 second. The green areas in the contour diagrams indicate that two-way crossing is suggested by the proposed GA procedure in those volume combinations.

Figure 6.7 Contour Diagram of Scramble WALK Phase Lengths (Sec) when K=0

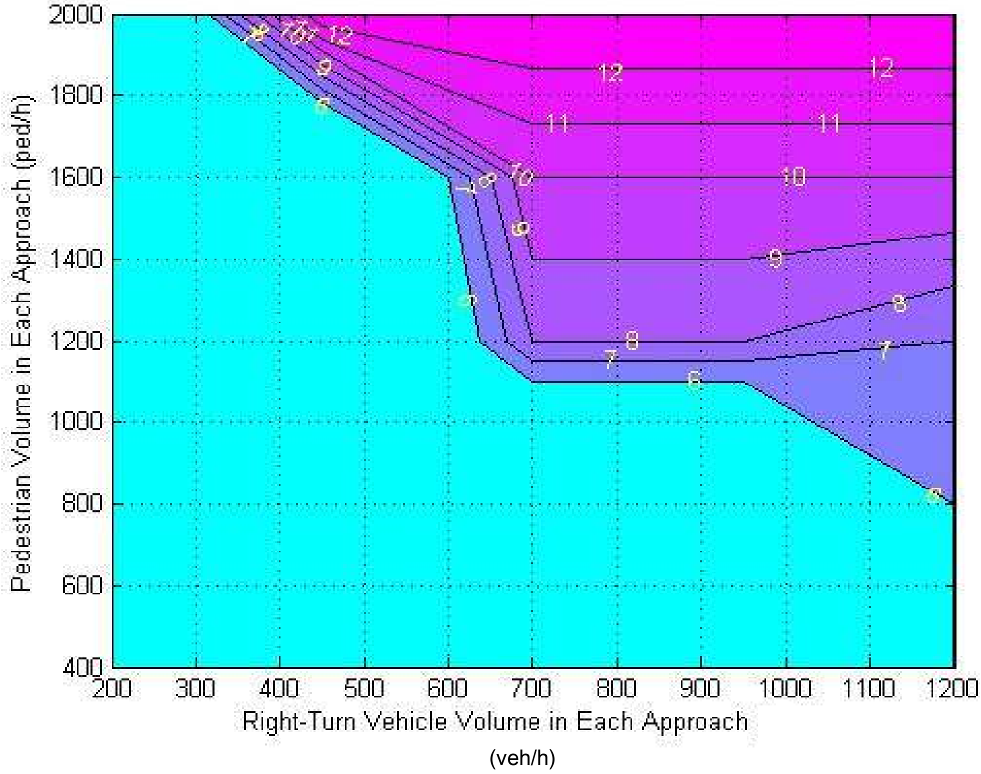


Figure 6.8 Contour Diagram of Scramble WALK Phase Lengths (Sec) when K=1

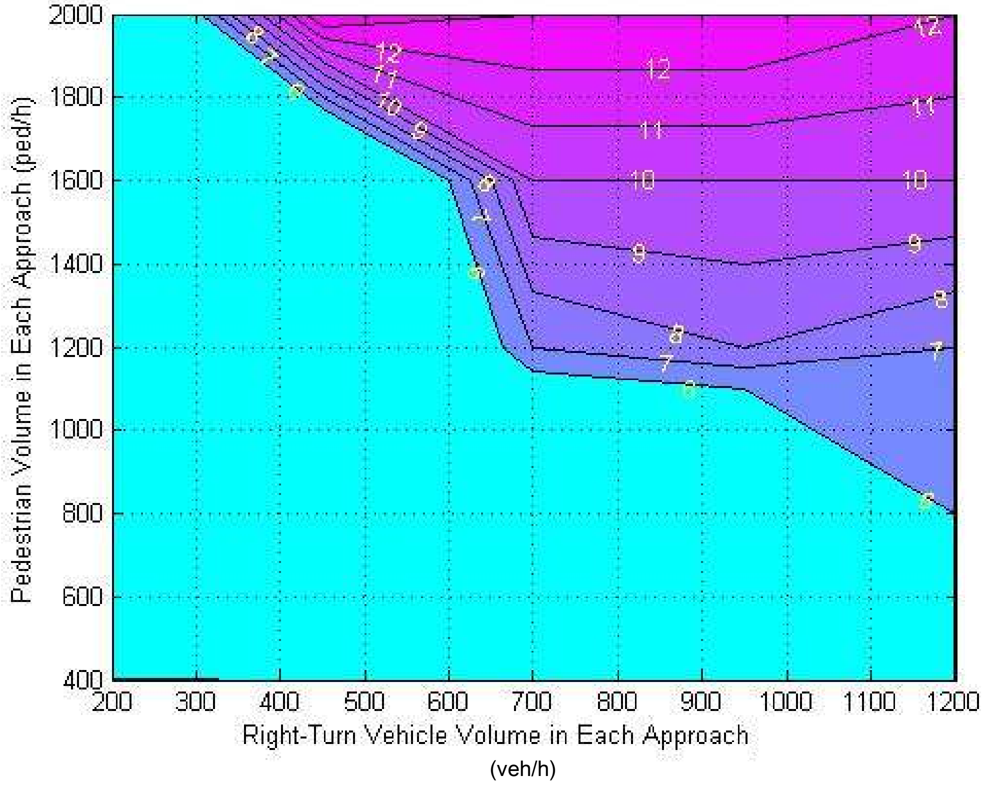


Figure 6.9 Contour Diagram of Scramble WALK Phase Lengths (Sec) when K=1.22

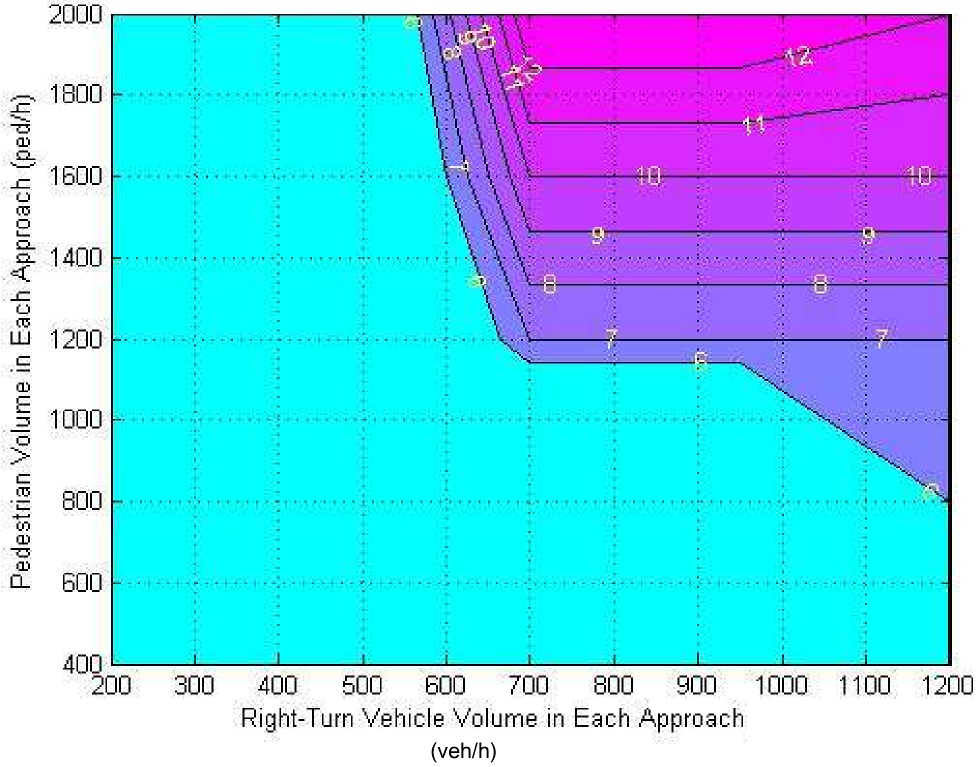
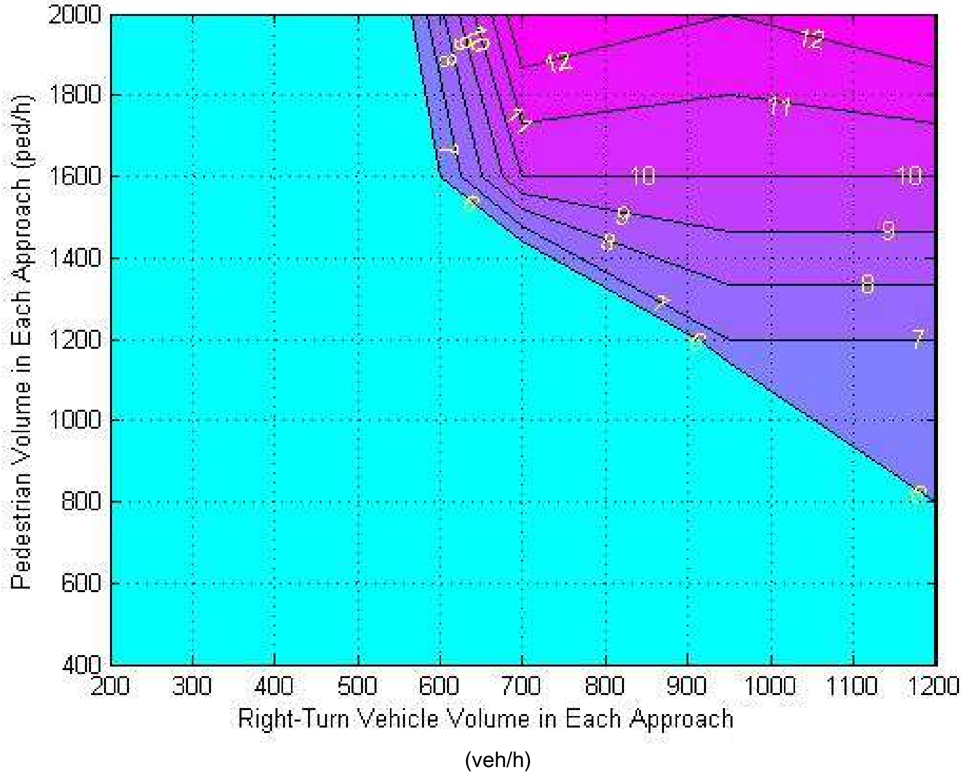


Figure 6.10 Contour Diagram of Scramble WALK Phase Lengths (Sec) when K=3



As illustrated in the figures, the distribution of scramble WALK phase length is not very sensitive to different relative time values. There is no significant difference between Figures 6.7 (K=0) and 6.8 (K=1), neither between Figures 6.3 (K=2) and 6.10 (K=3), probably because vehicle delay overwhelms pedestrian delay only with its uniform delay, and thus the change of pedestrian relative time value does not have a significant impact. However, some differences exist between Figures 6.8 (K=1), 6.9 (K=1.22) and 6.3 (K=2), probably due to the accumulative relative time value influence on signal timing since K = 0. The threshold for the pedestrian crossing pattern (to switch from two-way crossing to scramble crossing) shifts higher with the increment of the relative time value from 1 to1.22 and from 1.22 to 2. Additionally, most differences occur near the boundary of blue area (scramble crossing is appropriate) and green area (two-way crossing is appropriate).

When K is higher, which means that pedestrians are more favored at an intersection, it takes higher vehicle or pedestrian volumes for scramble crossing to be chosen as the appropriate pedestrian crossing pattern. It can be explained that a signal plan with a shorter cycle length and two-way crossing helps pedestrians to have less waiting time per cycle. Therefore, pedestrians are favored, and the request for scramble crossing is postponed to be responded till higher volumes arrive at the intersection.

On the other hand, when K is lower, which means that vehicles are more favored at an intersection, it takes lower vehicle or pedestrian volumes for scramble crossing to be chosen as the appropriate pedestrian crossing pattern. It can be explained that a signal plan with a longer cycle length and scramble crossing helps vehicles, especially right-turn vehicles, not to have the delay caused by interfering pedestrians in the intersection. Therefore, pedestrians are favored, and the request for scramble crossing is advanced to be responded when lower volumes arrive at the intersection.

In conclusion, the impact of relative time value on the optimal signal plans is important, when the difference of total user time between the two pedestrian crossing patterns is not substantial, e.g. the boundary area. In other situations, the impact is minor: with higher K, the scramble WALK phase length tends to be slightly lower because of the similar reasons mentioned above.

6.5 Impact of Initial Queues

In Section 6.5, tests are run to explore the impact of initial queues (Q_b) on optimal signal plans. The optimization results of three different initial queue settings are compared. In order to simplify the notation, the scenario with zero initial queues is represented by Scenario A. The scenario with fixed initial queues, no matter how much vehicle volumes are, (5 vehicles for all left movements, 10 vehicles for all through movements, 5 vehicles for all right movements) is represented by Scenario B. The scenario with initial queues varying with vehicle volumes is represented by Scenario C. As shown in Table 6.11, Scenario C makes approximate half of the vehicle volumes in one cycle remain in initial queues (assuming default cycle length is 90 seconds).

Table 6.11 Initial Queues of Various Vehicle Volumes in Scenario C

Vehicle Volume (veh/h)	**Initial Queue (veh)**
200	3
450	6
700	9
950	12
1200	15

The proposed GA procedure is used to generate appropriate pedestrian crossing patterns and scramble WALK phase lengths based on combinations of different right-turn vehicle volumes and pedestrian volumes. The traffic pattern combinations are based on the traffic characteristics shown in Table 6.5 with the following setting of Variable X, Y, and Z:

- ✧ All four pedestrian volumes (Variable Z) vary with the same amount from 400 to 2000 with an increment of 400 (ped/h).
- ✧ All four right-turn vehicle volumes (Variable X) vary with the same amount from 200 to 1200 with an increment of 250 (veh/h).
- ✧ All four through vehicle volumes (Variable Y) remain at 700 (veh/h).

Table 6.12 is the running result of the proposed GA procedure for the 75 different combinations of volumes under 3 different initial queue settings. The table shows which pedestrian crossing pattern is more appropriate and how the pedestrian scramble WALK phase length changes (if the scramble crossing is recommended). The scramble WALK phase length in each volume combination is acquired from the median value of the minimal user times by 5 different random seeds, and is rounded up to the closest integer.

Table 6.12 Scramble WALK Phase Length

Suggested by Proposed GA Procedure in Initial Queue Impact Analysis Tests

Scenario A			**Scenario B**			**Scenario C**		
X	**Z**	**Phase Length**	**X**	**Z**	**Phase Length**	**X**	**Z**	**Phase Length**
200	400	0	200	400	0	200	400	0
200	800	0	200	800	0	200	800	0
200	1200	0	200	1200	0	200	1200	0
200	1600	0	200	1600	0	200	1600	0
200	2000	0	200	2000	0	200	2000	0
450	400	0	450	400	0	450	400	0
450	800	0	450	800	0	450	800	0
450	1200	0	450	1200	0	450	1200	0
450	1600	0	450	1600	0	450	1600	0
450	2000	0	450	2000	14	450	2000	0
700	400	0	700	400	0	700	400	0
700	800	0	700	800	0	700	800	0
700	1200	0	700	1200	7	700	1200	7
700	1600	10	700	1600	10	700	1600	10
700	2000	13	700	2000	13	700	2000	13
950	400	0	950	400	0	950	400	0
950	800	0	950	800	0	950	800	0
950	1200	7	950	1200	8	950	1200	7
950	1600	10	950	1600	10	950	1600	10
950	2000	13	950	2000	13	950	2000	13
1200	400	0	1200	400	0	1200	400	0
1200	800	6	1200	800	6	1200	800	6
1200	1200	7	1200	1200	7	1200	1200	7
1200	1600	10	1200	1600	10	1200	1600	10
1200	2000	12	1200	2000	13	1200	2000	13

Figures 6.11, 6.3, and 6.12 are the contour diagrams of scramble WALK phase lengths in Table 6.12 under Scenario A, B, and C respectively. The contour diagrams are all based on a scale: 0 and 6 to 14 with an increment of 1 second. The green areas in the contour diagrams indicate that two-way crossing is suggested by the proposed GA procedure in those volume combinations.

Figure 6.11 Contour Diagram of Traffic Condition in Scenario A

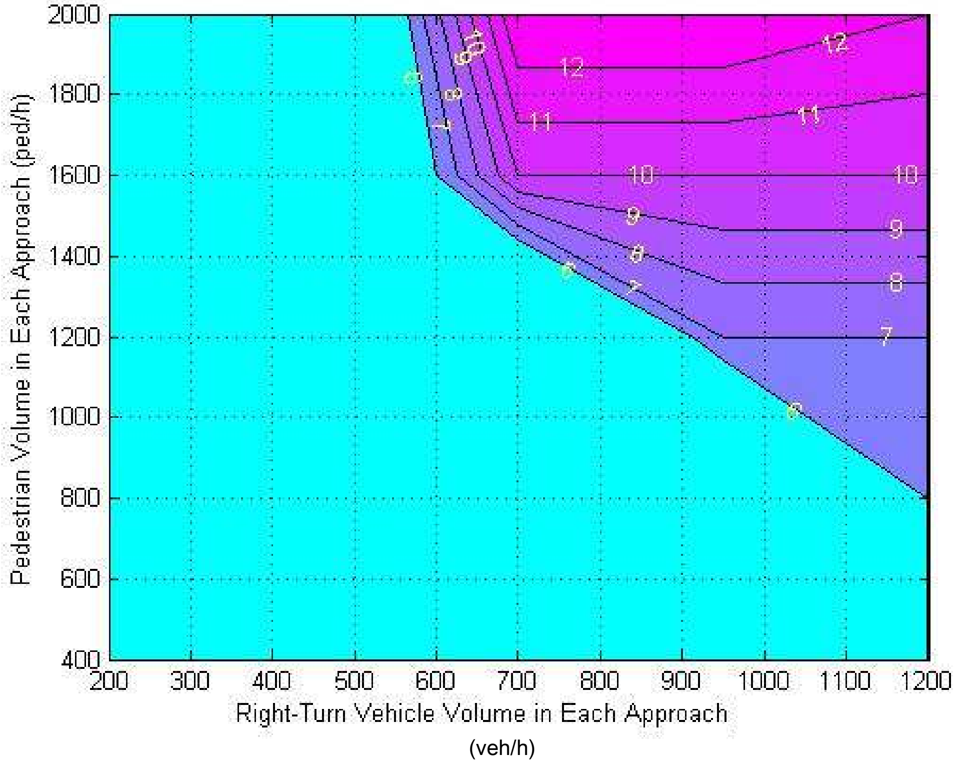
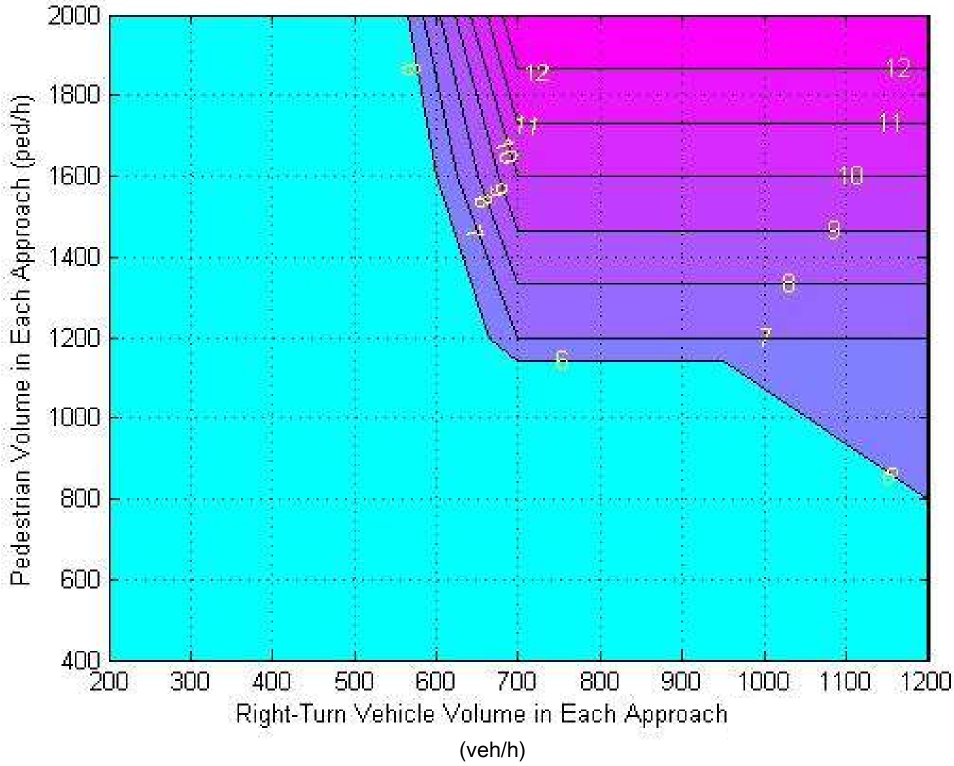


Figure 6.12 Contour Diagram of Traffic Condition in Scenario C



By comparing Figures 6.11 and 6.3, when right-turn vehicle volumes are high (>1000 veh/h), Scenario A tends to have slightly lower scramble WALK phase lengths than Scenario B. It can be explained that Scenario A has no initial queue delay but Scenario B has. Thus, with the same combination of pedestrian and vehicle volumes, Scenario A favors pedestrians more and tends to choose a lower scramble WALK phase length (so that pedestrians have less waiting time per cycle).

By comparing Figures 6.3 and 6.12, Scenario B tends to have lower scramble WALK phase lengths than Scenario C, and the threshold for the pedestrian crossing pattern (to switch from two-way crossing to scramble crossing) is higher. Such phenomena can be explained that Scenario B has shorter initial queues and therefore smaller initial queue delay than Scenario C when vehicle volumes are high. Thus, with the same combination of pedestrian and vehicle volumes, Scenario B favors pedestrians more, tends to choose a lower scramble WALK phase length (so that pedestrians have less waiting time per cycle), and shifts the threshold higher. Although Scenario B has longer initial queues than Scenario C when vehicle volumes are low, the ratios of volume to capacity (X) are less than one, and initial queues are able to be dissipated. Therefore, the slightly larger initial queue delay does not have a significant influence on the final result.

In conclusion, initial queues have a moderate impact on the optimal signal plans. It is easier and quicker for a traffic engineer to decide a suitable pedestrian crossing pattern and scramble WALK phase length according to contour diagrams. However, the result is more accurate by running the GA procedure with specific traffic volumes and initial queues.

6.6 Advantages in the Application of the Proposed GA Procedure

The proposed GA procedure has several advantages in speed, flexibility, and accuracy, which would be prominent during its application.

Firstly, the proposed GA procedure runs efficiently. It takes less than half a minute for the proposed GA procedure to run 50 generations with 5 different random seeds in Matlab, while it takes HCS GA around 3.5 minutes to run 50 generations with only one random seed.

Secondly, the proposed GA procedure is flexible, and therefore can be used in different intersections under different circumstances. The variation includes geometric design of the intersection, vehicle and pedestrian volumes, initial queues, and other traffic relevant parameters. Thus, the signal plan selected by the GA procedure would be the suitable solution particularly for that intersection with those traffic characteristics.

Moreover, although the analysis period is set as 15 minutes in the tests, it can be set as any positive values, such as 10 minutes, 5 minutes, or 2 minutes. The shorter the analysis period is, the faster the signal plan responds to the change of traffic demands. With a cycle-length-long analysis period, the GA procedure can realize real time signal plan optimization. However, frequent switches between two pedestrian crossing patterns and big signal timing difference between adjacent cycles should be avoided. Otherwise, either one of them can cause the confusion of both drivers and pedestrians, which might bring severe safety issues.

In addition, if an object-oriented platform can be set up, the application of the proposed procedure would be even more user-friendly and easier to use.

Chapter 7

Conclusions and Recommendations

Chapter 7 states the conclusion and recommendations for further research.

7.1 Conclusions

A GA optimization procedure is developed in this thesis to optimize signal timing of an individual intersection by minimizing total user time which considers both vehicle and pedestrian delay.

In order to verify the proposed optimization procedure, the impact of vehicle and pedestrian volumes on signal plans is tested in a hypothesized intersection. Signal plans selected by the GA procedure are reasonable. Phase lengths increase with the growth of the corresponding critical vehicle or pedestrian volumes. Furthermore, the pedestrian crossing type changes from two-way to a scramble crossing when corresponding pedestrian and vehicle volumes grow considerably. Moreover, in most cases of two-way crossing, it is inefficient to set a pedestrian green time, including WALK and DONT WALK phases, larger than the vehicle effective green time in the same moving directions. Only in cases with comparable total user times for two-way crossing and scramble crossing, there could be minor pedestrian green time leading or lagging vehicle green time.

Compared with Highway Capacity Software (HCS) GA function, the proposed procedure has the same accuracy and more capabilities. When there is no pedestrian at the intersection, with the same input, the total delay from HCS and the proposed GA procedure has no significant difference (<0.2%) before optimization. After optimization, the signal plans recommended by the proposed procedure can result in delay values that are slightly less than or at least as much as the delay values from the HCS GA optimized signal plans. However, when pedestrian delay is considered in signal timing, such a comparison could not be made because the HCS does not compute a delay for pedestrians, while the proposed GA procedure does.

In this thesis, contour diagrams and tables are generated as the selection guides for traffic engineers about which pedestrian crossing pattern, two-way crossing or scramble crossing, is more appropriate in certain situations and what appropriate scramble WALK phase length is needed when scramble crossing is suggested.

When a traffic engineer is considering the appropriate pedestrian crossing pattern for an intersection, not only pedestrian volumes and right-turn vehicle volumes need to be taken into account, but also through (and left-turn) vehicle volumes. Scramble crossing is beneficial when pedestrian and right-turn vehicle volumes in an approach are high but through vehicle volumes are relatively lower.

7.2 Recommendations for Future Research

This section discusses the possible areas for further research, for example, expanding the object of the GA procedure to a network or arterial, and considering other transportation users (e.g. cyclists and buses) in the total user time model.

7.2.1 Network or Arterial Signal Optimization

The proposed GA procedure is only capable to optimize signal plans for an individual intersection. However, there might be several intersections that need to be optimized by minimizing the total user time of both vehicles and pedestrians, especially in a central business district. Therefore, expanding the object of the GA procedure from an individual intersection to a network or arterial could be one of the areas for further research.

Virkler (1998) discussed the methodology to calculate pedestrian walking time on links in his research "in Prediction and Measurement of Travel Time along Pedestrian Routes". He estimated walking time based on average pedestrian space, because he found pedestrian speed depending on average pedestrian space (m^2/ped) which is the reciprocal of pedestrian density. Virkler also claimed that pedestrian speed is approximately normally distributed at a given pedestrian density.

Moreover, the concept of pedestrian progression was also proposed in some researches. Virkler (1998) discussed in his research "Signal Coordination Benefits for Pedestrians" that if pedestrian platoons were found due to upstream signals, the pedestrian delay at downstream signals could decrease greatly by employing a suitable signal coordination plan. Chilukuri and Virkler (2005) proved that the pedestrian delay calculation which assumes random arrivals might not be accurate in a coordinated arterial. Therefore, Bhattacharya and Virkler (2005) studied cyclic flow profiles generated from arrival patterns and developed a method to estimate the delay from the offset with respect to the upstream signal cycle. Then they used the method to determine favorable signal offsets for pedestrian progression.

In summary, future research can explore to expand the object of the GA procedure from an individual intersection to a network or arterial. Furthermore, walking time on links and pedestrian progression could be considered in a network or arterial.

7.2.2 Other Transportation User Time

The proposed GA procedure considers pedestrian and vehicle delay in the total user time. However, there are other transportation users as well, e.g. cyclists and buses. Therefore, including the delay of other transportation users into the total user time could be one of the areas for further research.

The new total user time model can be expressed as follows:

$$UT = UT' + K_c \cdot T \cdot \frac{TD_c}{3600} + K_b \sum_{i=1}^{12} [V(i) \cdot T \cdot \frac{D_b(i)}{3600} \cdot n_b]$$

Where UT = total user time in the analysis period (h)

UT' = total vehicle and pedestrian user time in the analysis period (h), result of the equation in Section 3.1.1

T = duration of the analysis period (h)

K_c = relative time value of a cyclist compared with a passenger car

TD_c = total cyclist delay in the analysis period (s)

K_b = relative time value of a bus compared with a passenger car

n_b = average vehicle occupancy per bus

V(i) = bus adjusted volume in lane group i (veh/h)

$D_b(i)$ = average delay per bus in lane group i (s)

The calculation of TD_c can be similar to that of pedestrian or vehicle total delay. It depends on transportation regulation or infrastructure design – whether cyclists are treated like pedestrians or vehicles.

With the new total user time model, the GA procedure would be able to find the optimal signal plans with the minimal total user times of all the transportation users (vehicles, pedestrians, cyclists, and buses) in different situations.

7.2.3 Other Areas

Future research can also explore to add abilities to deal with intersection geometric layouts with shared lanes, signal plans with permitted left-turn phases and right-turn on red permission, the impact of pedestrian platoon interaction, and pedestrian safety issue.

The proposed GA procedure is only capable to optimize signal plans in an intersection with exclusive lanes. However, shared lanes are commonly used in the real world, and thus they need to be considered, including right-turn and through shared lanes, left-turn and through shared lanes, and shared lanes of all the three movements. The ability of the GA procedure to process intersection geometric layouts with shared lanes could be one of the areas for further research.

The proposed GA procedure is only capable to optimize signal plans with protected left-turn phases and regulation that no right-turn on red is allowed. However, permitted left-turn phases and right-turn on red permission need to be considered and better optimal signal plans, i.e. signal plans with lower total user time, might be acquired after the GA procedure is run. Therefore, the ability of the GA procedure to process permitted left-turn phases and right-turn on red permission could be one of the areas for further research.

The proposed GA procedure does not consider the impact of pedestrian platoon interaction. However, pedestrian delay on crosswalks, caused by the interactions of pedestrian platoons, is considered in the research by Li, et al. (2009). They believed that crossing time increased with the increment of pedestrian demands on both sides of the crosswalk, due to the interaction between conflicting pedestrian flows. Thus, they considered the impact of bi-directional pedestrian flow on crossing time, speed on signalized crosswalks, and the resultant pedestrian delay. In addition, they also considered the discharging delay for standing pedestrian queue on sidewalks. Therefore, considering the impact of pedestrian platoon interaction could be one of the areas for further research.

The total user cost model does not consider pedestrian safety. However, by separating pedestrians from the vehicle flow, one of the major benefits of scramble crossing is additional pedestrian safety, which has to be considered if the signal timing of an intersection is evaluated from a comprehensive perspective. Therefore, quantifying pedestrian safety and adding it into the total use cost model could be one of the areas for further research.

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