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## **ABSTRACT**

### **OPTIMIZATION OF URBAN TRAFFIC CONTROL STRATEGIES BY A NETWORK DESIGN MODEL**

**by  
Wu Sun**

The efficiency of congested urban transportation networks can be improved by implementing appropriate traffic control strategies, such as signal control timing, turning movement control, implementation of one-way traffic policies, lane distribution controls etc.. In this dissertation, the following strategies are addressed: 1) Intersection left turn addition/deletion, 2) Lane designation, and 3) Signal optimization.

The analogy between the network design problem (NDP) and the optimization of traffic control strategies motivated the formulation of an urban transportation network design problem (UTNDP) to optimize traffic control strategies. An UTNDP is a typical bi-level programming program, where the lower level problem is a User Equilibrium (UE) traffic assignment problem, while the upper level problem is a 0-1 integer programming problem. The upper level of an UTNDP model is used to represent the choices of the transportation authority. The lower level problem captures the travelers' behavior. The objective function of the UTNDP is to minimize the total UE travel time. In this dissertation, a realistic travel time estimation procedure based on the 1997 HCM which takes account the effects of the above factors is proposed.

The UTNDP is solved through a hybrid simulated annealing-TABU heuristic search strategy that was developed specifically for this problem. TABU lists are used to avoid cycling, and the Simulated Annealing step is used to select moves such that an

annealing equilibrium state is achieved so that a reasonably good solution is guaranteed.

The computational experiments are conducted on four test networks to demonstrate the feasibility and effectiveness of the UTNDP search strategy. Sensitivity analyses are also conducted on TABU list length, Markov chain increasing rate and control parameter dropping rate, and the weight coefficients of the HEF, which is composed of the current link v/c ratio, the historical contribution factor, and the random factor.



**OPTIMIZATION OF URBAN TRAFFIC CONTROL STRATEGIES  
BY A NETWORK DESIGN MODEL**

**by  
Wu Sun**

**A Dissertation  
Submitted to the Faculty of  
New Jersey Institute of Technology  
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## APPROVAL PAGE

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To my parents

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# **CHAPTER 1**

## **INTRODUCTION**

### **1.1 Problem Identification**

One of the main problems transportation engineers and planners are facing in most urban areas is the rapid growth of congestion. Congestion is typically observed during the morning and evening peak periods. However, in most metropolitan areas, congestion extends to the “off-peak” periods as well. The main cause of congestion in urban areas is the unavailability of adequate capacity to handle the demand. Congestion causes travelers to spend more time per trip, which may result in lower productivity, increase in noise, and air pollution. How to alleviate congestion and improve the efficiency of the transportation system are among the top priorities of both transportation researchers and practitioners.

The efficiency of congested urban transportation networks can be improved by physical expansion of the network or by increasing the capacity of the existing infrastructure through traffic control strategies and traffic demand management techniques. Physical expansion of the network includes addition of new roads, capacity enhancement of road segments and improvement of intersections. Unfortunately, in most urban areas, expansion of the existing road system is reaching its physical limits, either due to the lack of right of way or the acquisition of right of way is prohibitively expensive. Network efficiency can also be improved by appropriate traffic demand management techniques including flexible work schedules, reallocation of trip attraction centers, real time traffic information telecommuting, etc.. Another option to alleviate

congestion is by implementing appropriate traffic control strategies, such as signal control timing, turning movement control, implementation of one-way traffic policies, lane distribution controls etc.

Transportation professionals have been providing solutions to traffic control problems since the existence of vehicles. The grid system became the most popular network configuration, especially for urban systems. Another popular configuration is the arterial system. In each case, the system operator “forces” the users to select or avoid certain paths by optimizing signal settings or re-configuring network links, in order to minimize either network-wide delays, specific sections of the network, specific intervals, or signal intersections. Often, safety concerns at a specific intersection, arterial or network become the determining factor for the design of the specific facility, and transportation efficiency then takes a secondary vote. The strategy followed by transportation professionals is one that falls under a system optimal strategy. The re-configuration of network links includes lane designation control, one-way/two-way traffic control, and intersection movement control. Lane designations in a transportation network are orientated to better accommodate the traffic flows on the paths followed by the drivers during the peak periods of the day. Appropriate intersection movement controls can reduce conflicts caused by turning movements at intersections. Similarly, one-way streets are selected to eliminate the conflicts between left turn movements and through movements at intersections. In one-way streets, left turns become similar to right turns. The decision to favor certain paths by selecting appropriate signal timings to minimize network-wide delays is one form of prioritizing the origin-destination (O-D) matrix.



In arterial signal timing, some of the most popular software used in the U.S. are PASSER II-90, TRANSYT-7F and MAXBAND. PASSER II-90 and MAXBAND try to optimize the bandwidth of the progression, providing priority to the users of the arterial rather than the cross streets. TRANSYT-7F optimizes its performance index (PI) which minimizes the total travel time and the number of stops, thereby, providing a more balanced distribution of the right-of-way to the arterial users and the cross street users. TRANSYT-7F is also used to optimize the signal timing of urban networks using the same PI. One critical deficiency of these softwares is that they do not consider the user behavior in their signal optimization procedures. It is well demonstrated, however, that users try to optimize their own path travel times that may differ from the way these softwares attempt to impose on the travelers. There exists a gap in the transportation planning process in traffic control strategies between the existing signal optimization and the traffic assignment. This research provides a methodology to bridge the gap and provides an integrated traffic control optimization strategy, taking into consideration the user behavior that is represented by a user equilibrium traffic assignment procedure.

The analogy between the network design problem (NDP) and the optimization of traffic control strategies motivated the formulation of an Urban Transportation Network Design Problem (UTNDP) model to optimize traffic control strategies. In this dissertation, a systematic approach of optimizing traffic control strategies is proposed to improve the efficiency of an urban transportation system, without capital construction expenditures. Specifically, the following strategies are included within the UTNDP: 1) left turn and right turn additions/deletions, 2) lane designation, and 3) signal optimization

which takes into account the users' behavior. These control strategies are better depicted, for a typical 4-leg intersection with 2 lanes in each direction, in Figure 1.1.

The decision variables for the first two types of control strategies are discrete in nature, either add/delete an abstract link (e.g. left turn) or increase/decrease number of lanes on a physical link (e.g. 2 to 3 or 1 lanes). The decision variables for signal optimization: cycle length, green split and offsets are continuous, as are the link traffic flows of the UE traffic assignment. The combination of signal optimization and lane designation primarily changes the capacity of the available movements in the transportation network. The UE based link flows are the users' response to the new transportation network configuration.

## **1.2 Characteristics of the UTNDP (Urban Transportation Network Design Problem) Model**

Urban transportation systems fall under the category of large-scale systems. In an urban area, the number of intersections, which are represented by nodes in a network representation, often exceeds several hundreds or thousands. The number of road segments (also known as links in network representation) connecting adjacent intersections or interchanges is even larger than the number of nodes. The process of defining a transportation system is subject to the decision of planners, the politicians, the developers, the people and the physical characteristics of the area. Often, these groups have conflicting objectives, such as minimize the total network travel time, improve safety, improve air quality etc. The large size and the complexity caused by conflicting objectives of different interest groups make it difficult to define transportation network

problems in a mathematical form. Often only one or a few objectives appear in the formulation in an effort to simplify the problem.

An UTNDP can be formulated as a typical bi-level programming program, where the lower level problem is a traffic assignment problem, while the upper level problem is usually a 0-1 integer programming problem. At the lower level of an UTNDP, a traffic assignment model is formulated that can capture travelers' choice of route, mode, origin-destination etc. to produce the link flows based on the current network configuration. Wardrop's (10) two traffic assignment conditions, also known as user equilibrium (UE) condition and system optimal (SO) condition have been most commonly used. The UE principle is best described as a variational inequality problem (VIP), although when the link interactions are symmetric, it also can be formulated as a minimization mathematical program. The upper level of an UTNDP model is used to represent the transportation planner's choice. The discrepancy of the objective functions of the lower and the upper level problems makes the solution procedure extremely computational demanding. Given a transportation network, the addition of new facilities (e.g. new links) or extra capacity on the existing links may increase the total network travel time as well as the individual path travel time from an origin to a destination, a phenomenon most widely known as Braess's "Paradox" (5).

Another complexity in transportation network analysis is the presence of link interactions, which can be either symmetric or asymmetric. As stated before, the UE principle can be best described as a VIP. The VIP formulation is a general form of mathematical formulation, which applies to both symmetric and asymmetric link interaction cases. Link interactions are of interest because the travel time of a link

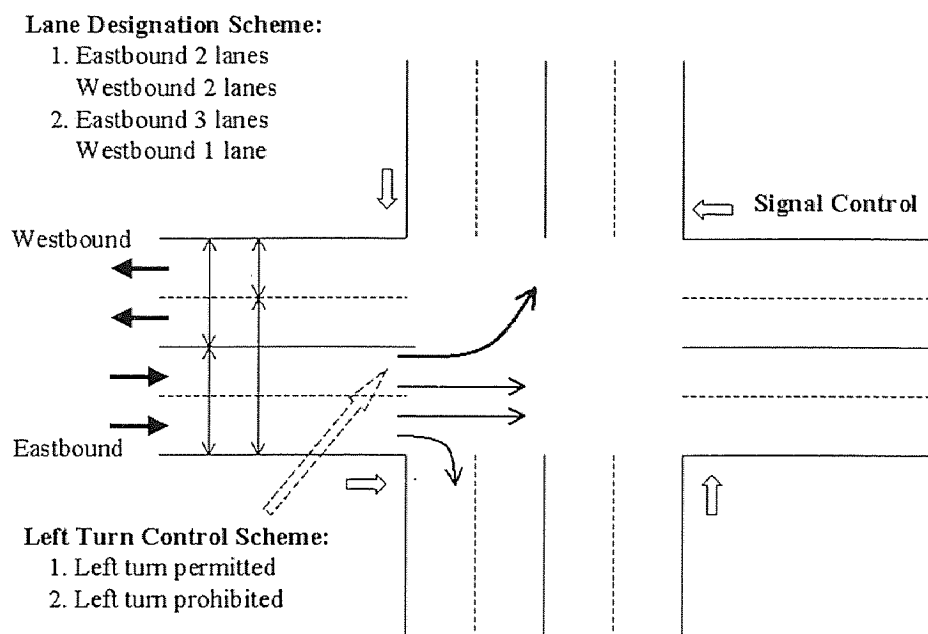
usually depends on the flows of adjacent conflicting links, especially under congested conditions. If the travel time on a given link depends only on the flow on that link and not on the flows on any other links, then there are no link interactions among these links, and the problem is symmetric. However, in urban transportation systems, due to heavy two-way traffic, unsignalized intersections and left movements at signalized intersections, link interactions can not be ignored. According to Sheffi (5), “when the link interactions are symmetric, the marginal effect of one link flow, say  $x_a$ , on the travel time on any other link, say  $t_b$ , is equal to the marginal effect of  $x_b$  on  $t_a$ ”. In the symmetric case, the equilibrium flow pattern can be found by solving an equivalent minimization mathematical program. In the asymmetric case, which can not be formulated as a minimization mathematical program, the problem is formulated as a variational inequality problem (VIP). Only direct algorithms are known to solve the asymmetric problem such as the diagonalization algorithm (5).

The most commonly used objective in transportation network design problems is the total travel time of the network. Travel time not only varies with traffic volume, but also varies with the network configuration that includes traffic control patterns, such as signal timing, lane designations, intersection movement controls and geometric characteristics. In general there are two types of travel time functions, the Bureau of Public Roads (BPR) type curves (55) which are applicable for freeway type links and the delay formulas for signalized intersections such as the one used in the 1997 Highway Capacity Manual (46). The most commonly used travel time estimation function in traffic assignment is the BPR curve. Although the BPR type curves do reflect the influence of traffic volume on the travel time, it does not capture the effect of traffic

control strategies in a realistic manner. Berka et al. (13) proposed a more realistic travel time estimation procedure. In their procedure, both traffic volume and control patterns were taken into consideration. However, one important factor, the progression of traffic flows is not included in Berka et al.'s procedure. In transportation networks, especially in urban arterial systems, vehicles move from one intersection to the next in a platoon format, and the platoon affects the delay at the next intersection. When the intersections are treated separately, the progression effect is not taken into consideration by travel time estimation procedure. It is more appropriate to consider intersection signal timings in a coordinated way to account for the effect of progressions, which necessitates the optimization of offsets between adjacent intersections. A good pattern of signal settings with appropriate offsets for adjacent intersections could reduce congestion, and increase network-wide performance. In this dissertation, a travel time estimation procedure that takes progression effects into account is proposed.

There are three types of decision variables in the UTNDP. The decision variables (addition/deletion of links) of lane designations and intersection movement controls of the UTNDP model are discrete. The decision variables are considered and depicted in Figure 1.1.

- adding/deleting left turn movement at an intersection,
- adding one lane in one direction of a two-way link (this implies that one lane from the opposite direction will be deleted),
- deleting one lane from a link (this implies that one lane from the opposite direction will be added)



**Figure 1.1** Traffic Control Strategies

In the process of lane addition/deletion, the lane designations and the intersection movement control strategies will change, and consequently the signal timings need to be changed. Signal timings constitute another type of decision variables, including the cycle time (the same for the whole network), green splits, and offsets. Signal timing is one of the main factors that affects the link performance functions. Any change in the decision variables, addition or deletion of a link, essentially changes the geometry of an approach or the intersection as a whole. Thereby, the signal timing needs to be adjusted based on the new network configuration. At each iteration of the solution procedure, due to the

addition/deletion of links, the signal timing changes and consequently the link performance functions need to be updated at each iteration. The last type of decision variables is the link flow variable that is obtained by solving the lower level UE traffic assignment problem in an UTNDP. Link flows are affected by lane designations, intersection movement controls, and signal settings. The updates of lane designations and intersection movement controls are based on the Simulated Annealing TABU Search heuristic that is described in Chapter 3. Signal settings are obtained by solving a non-linear programming model that includes capacity constraints that are dependent on the link flows.

### **1.3 Research Objectives**

The primary objectives of this dissertation are the formulation and development of a heuristic search strategy to solve a transportation network design problem by optimizing traffic control strategies in urban signalized networks. The specific objectives of the problem are:

- 1) Formulate the traffic control optimizing strategy as an UTNDP model.
- 2) Develop a heuristic search strategy to solve the UTNDP
  - Develop a traffic assignment procedure to find the flows on signalized network.
  - Identify a signal optimization procedure.
  - Perform computational experiments to demonstrate the feasibility and effectiveness of the UTNDP search strategy on small size urban networks.

## 1.4 Overview

In Chapter 2, the literature review on both the formulation and solution algorithms of NDP models is presented. The problem formulation is introduced first, followed by the link performance functions that are used for estimating link travel times. Since the UTNDP is a bi-level programming problem with the lower level problem as an UE traffic assignment problem, literature on traffic assignment is also introduced, followed by the algorithms for both the upper and lower level problems. The last section of Chapter 2 presents a review on network representation that is the basis of any network analysis. In Chapter 3, the UTNDP methodology is outlined, which includes the bi-level model formulation and the proposed solution strategy. In Chapter 4, the flowcharts and the corresponding main subroutines of the heuristic search procedure are presented, including the heuristic evaluation functions, and the updating criteria. In Chapter 5, numerical experiments are presented on four test networks. Conclusions and recommendations on future work are presented in Chapter 6.



## CHAPTER 2

### LITERATURE REVIEW

An UTNDP is a typical bi-level programming problem, where the upper level problem is a 0-1 integer programming problem, and the lower level problem is a traffic assignment problem. This literature review addresses both of these problems which are presented in the following sections together with existing solution algorithms and heuristics.

Literature on performance functions (travel time functions) and network representations that are critical to the formulation and solution of UTNDP models are also presented.

#### 2.1 The Formulation of Network Design Problem

An NDP falls into the category of the Stackelberg game (17), which is a well-studied field in operations research. Stackelberg games characterize a behavioral model of two players. One player (the leader) wants to optimize a certain objective, and s/he knows how the other player (the follower) will respond to any decisions s/he makes. If neither player can improve his/her objective by unilaterally changing his/her decision, then an equilibrium state is reached. Four important references on NDP are LeBlanc (1), Magnati and Wong (14), Friesz (8) and LeBlanc and Boyce (4). Magnati and Wong (14) provided an extensive review on both continuous and discrete NDP models. The relationship between NDP and other transportation network analysis problems was also discussed in their paper. Friesz (8) provided a comprehensive review on transportation network design problems and discussed the research opportunities in this field. In the next sections the formulation proposed by LeBlanc and Boyce (4) and LeBlanc (1) are

presented. First, the relationship between the NDP and the Stackelberg game is introduced.

### 2.1.1 An Introduction to NDP

An NDP is a typical Stackelberg game or leader-follower game that can be mathematically formulated as shown by Fisk (17):

For a given strategy of player 2, player 1's optimal strategy is found by solving:

$$\min_{x_1} P_1(x_1, x_2) \quad (2.1)$$

At equilibrium state  $(x_1^*, x_2^*)$ :

$$P_1(x_1, T(x_1)) \geq P_1(x_1^*, T(x_1^*)) \quad (2.2)$$

$$P_2(x_1, T(x_1)) \leq P_2(x_1, x_2) \quad (2.3)$$

where,

$x_i$  the decision variables of player  $i$ ,  $i = 1, 2$ ,  $x_i \in \varphi_i$ ,

$P_i(\cdot)$  the performance function of player  $i$ ,  $i = 1, 2$ ,

$x_2 = T(x_1)$  is the response of player 2 for a given  $x_1$ ,  $T: \varphi_1 \rightarrow \varphi_2$ .

An NDP is a Stackelberg game equivalence in transportation application. The transportation authority wants to optimize network-wide operations, taking into account

the travelers' response to a specific network configuration. The transportation authority plays the leader role, while the travelers play the follower role. In this UTNDP, the transportation authority's (the leader) problem is to minimize the network-wide total travel time by optimizing traffic control strategies such as left turn additions/deletions, lane designation controls, and signal setting optimizations. In the UTNDP model, the traffic control strategy variables (the upper level decision variables) are equivalent to the  $x_1$  variables in the Stackelberg game, and the link traffic flow variables (the lower level decision variables), which are the responses of travelers to a given network configuration and traffic control strategies, are equivalent to the  $x_2$  variables in the Stackelberg game.

Similar to the UTNDP, optimal signal setting problems are also identified as Stackelberg games (17,38). The decision variables in a signal setting problem include cycle lengths, green splits, and offsets of adjacent intersections. Any changes of signal setting parameters result in changes of link performance functions, and they cause changes in traffic flow distribution patterns. Allsop (34) pointed out that the effect of the signal setting on flow distribution patterns should be taken into account in the traffic assignment process. In addition, Heydecker (18), Smith (33), Cantarella et al. (35) and Yang et al. (40) gave similar suggestions. The combined signal setting and traffic assignment problem is also referred to as equilibrium network traffic signal setting that can be solved by two approaches, global optimization models and iterative procedures. The global optimization models are continuous NDP models. Usually, among all signal setting parameters (i.e. cycle lengths, green splits, and offsets), only green splits are treated as decision variables, where all other parameters are assumed to be given. These models minimize network-wide travel time in terms of green splits and traffic flows

under a UE traffic flow pattern. There are two main disadvantages associated with these global optimization models. First, there are no existing efficient solution algorithms; second, this formulation ignores signal coordination among adjacent intersections that has significant influence on network performance. Cantarella et al. (35) proposed an iterative procedure named ENETS (Equilibrium Network Traffic Signal Setting) which has two consecutive signal setting steps, the single intersection signal setting step and the network coordination step. The iterative procedure allows all signal setting parameters to be treated as decision variables and has less computational requirements. However, the convergence of this procedure can not be guaranteed (20,37).

Since traffic engineers often decide not only to change the signal settings but also change the lane designations and the intersection movement controls, an UTNDP and an equilibrium network traffic signal setting problem often intertwine with each other. In this dissertation, the UTNDP is formulated in a way that it includes the equilibrium network traffic signal setting problem as an essential step in the whole procedure to optimize the signal settings and the network configuration simultaneously.

### **2.1.2 A Bi-Level Programming Model by LeBlanc and Boyce**

There are two types of decision makers in a Stackelberg game, the facility authority, which is also viewed as the upper level decision makers, and the facility users, who are viewed as the lower level decision makers. The interaction between these two types of decision-makers requires a formulation that can reflect the bi-level nature of a Stackelberg game such as an UTNDP. In 1986, LeBlanc and Boyce (4) formulated the UTP as a bi-level programming model as follows:

$$\min_{x_1} F(x_1, x_2) \quad (2.4)$$

where  $x_2$  is optimal for

$$\min_{x_2} f(x_1, x_2) \quad (2.5)$$

$$s.t. \quad G(x_1, x_2) \geq b \quad (2.6)$$

The objective  $\min_{x_1} F(x_1, x_2)$  is referred to as the upper level problem, and the lower level problem is defined as  $\min_{x_2} f(x_1, x_2)$  for fixed  $x_1$ . In an UTNDP,  $F(x_1, x_2)$  is the objective function which represents the network-wide total travel time, while  $f(x_1, x_2)$  is carefully constructed so that  $x_2$  is a user equilibrium flow pattern. The variables  $x_1$  in the upper level problem represent the control variables of network planners; the lower-level variables  $x_2$  represent the route-choice decisions of the network users. In an UTNDP problem,  $x_1$  is the decision variable vector of link additions/deletions,  $x_2$  is the flow pattern variable vector of the network.

LeBlanc and Boyce formulated a linear bi-level programming NDP model with user-equilibrium (UE) driver behavior and continuous link improvement variables. They defined the upper level objective function as the total travel cost which is the user cost per vehicle multiplied by the number of vehicles using the link. Then, they assumed the total travel cost on each link could be accurately measured with a piecewise linear function with  $M$  pieces or segments. The bi-level model was formulated as follows:

$$\min_y \sum_l \sum_m c_{lm} x_{lm} + \gamma \sum_l b_l y_l \quad (2.7)$$

where  $x$  is optimal for

$$\min_x \sum_l \sum_m \bar{c}_{lm} x_{lm} \quad (2.8)$$

subject to:

$$T_{ij} + \sum_{l \in B_i} x_l^j = \sum_{l \in A_j} x_l^j \quad \forall i, j \quad (2.9)$$

$$\sum_{m=1}^{M_l} x_{lm} = \sum_{j=1}^J x_l^j \quad \forall l \quad (2.10)$$

$$x_{lm} \leq K_{lm} + \alpha_{lm} y_l \quad \forall m, l \quad (2.11)$$

where

$M_l$  number of pieces or segments in the piecewise linear total travel cost

function for link  $l$ ,

$K_{lm}$  capacity of piece  $m$  of link  $l$ ,

$c_{lm}$  slope of piece  $m$  of link  $l$ ,

$x_{lm}$  flow on piece  $m$  of link  $l$ ,

$x_l$  total flow on link  $l$ ,

$J$  number of destination nodes,

$x_l^j$  flow on link  $l$  with destination  $j$ ,

$T_{ij}$  required number of trips between origin node  $i$  and destination node  $j$ ,

$A_i$  set of links pointing out of node  $i$  (after node  $i$ ),

$B_i$  set of links pointing into node  $i$  (before node  $i$ ),

$\alpha_m$  are exogenously specified parameters with  $\sum_m \alpha_m = 1$ ,

$b_l$  the unit cost of improvements on link  $l$ ,

$\bar{c}_{lm}$  the slopes of the piecewise linear integrals of the user-cost functions,

$y_l$  decision variable on link  $l$ ,

$\gamma$  constant.

Bard (21) has shown that any linear bi-level program can be solved by solving a single linear program and then by iteratively modifying the objective function and resolving it. When the network is within a reasonable size, the piecewise linear bi-level programming model should yield an exact solution. However, for larger networks with thousands of nodes or many linear pieces per link, the model can not be solved directly. In their paper, LeBlanc and Boyce suggested an efficient solution procedure for larger networks. They suggested using an equivalent optimization model in place of the linear program in Bard's algorithm. This equivalent optimization model can be solved very efficiently using the Frank-Wolfe algorithm. LeBlanc and Boyce's work was the first exact solution for the continuous NDP at that time. However, their model can only be applied to small size real world networks with continuous decision variables.

### 2.1.3 General Formulations of NDP (Network Design Problem) by LeBlanc and Abdulaal

LeBlanc was among the first ones to study the NDP. In 1975, he formulated a discrete NDP model (1) with fixed transportation demands as follows:

$$\min_y \sum_a t_a(x,y)x_a \quad (2.12)$$

subject to:

$$\sum_{a \in I} \beta_a y_a \leq B \quad (2.13)$$

$$x_a - My_a \leq 0 \quad \forall a, \quad a = 1, 2, \dots, n \quad (2.14)$$

$$y_a = (0,1) \quad \forall a, \quad a = 1, 2, \dots, n \quad (2.15)$$

$$x = (\dots, x_a, \dots) \quad (2.16)$$

where,

$t_a(x,y)$  the average transportation cost on arc  $a$ ,

$x_a$  the flow on arc  $a$ ,

$y = (\dots, y_a, \dots)$  is the decision variable vector of link additions/deletions,

$y_a$  unity if arc  $a$  is added to network, and 0 otherwise,

$\beta_a$  is the fixed cost of construction arc  $a$ ,

$B$  is the fixed link addition budget,



$M$  is a large constant,

$I$  is the set of arcs considered for addition to the network,

$n$  is the number of links in the network.

This is also a bi-level program. The objective function  $\sum_a t_a(x, y)x_a$  is the total travel time of the network. Constraint (2.13) is the budget constraint; (2.14) prohibits flow on links that are prohibited. The constraint (2.16) is the lower level of the bi-level program, which can be obtained from an equivalent minimization problem or a VIP.

In 1979, Abdulaal and LeBlanc (6) formulated a continuous model with fixed demand as follows:

$$\text{Min. } \sum_a t_a(x, y)x_a + w \sum_a \beta_a(y), \quad (2.17)$$

subject to:

$$y \geq 0, \quad (2.18)$$

where,

$y_a$  is the capacity enhancement of arc  $a$ ,

$y = (\dots, y_a, \dots)$  is the decision variable vector of capacity enhancement,

$\beta_a(y)$  is the cost of improving arc  $a$  as a function of  $y$ ,

$w$  is a dual variable for the budget constraint  $\sum_a \beta_a(y) \leq B$ ,

$B$  is the fixed budget for capacity enhancement,

All other notations are the same as the discrete model.

In this model, the budget constraint was put into objective by introducing Lagrangian dual variable  $w$ .

## 2.2 Link Performance Functions

Link performance functions, also known as link travel time functions, are mathematical models used to estimate the link travel times, as a function of traffic flow, geometric characteristics of the modeled facility and intersection signal settings and control strategies (13,31). The shape of performance functions is important because they have significant impact on both the computational tractability of the UTNDP and the existence and uniqueness of the solutions of the UE problem at the lower level. In general, the link travel time functions for controlled intersections consist of two components: the cruise time on the link and intersection delay. Link cruise time is the time of a vehicle travels from the beginning to the end of a link. Intersection delay considers the time a vehicle is delayed due to the control for the specific movement that a vehicle is trying to perform.

### 2.2.1 The BPR Type Curves (55)

The most well known link travel time function is the Bureau of Public Roads (BPR) curve. The BPR curve is more appropriate for freeway links rather than signalized streets, because it doesn't reflect the impact of delays caused by signal settings and turning movement controls at intersections. The BPR curve is presented below:

$$t_i = t_{i0} \left[ 1 + r \left( \frac{x_i}{c_i} \right)^k \right] \quad (2.19)$$

where,

$x_i$  traffic flow on link  $i$ ,

$t_i$  average travel time on link  $i$ ,

$t_{i0}$  free-flow travel time parameter for link  $i$ ,

$c_i$  capacity parameter for link  $i$ ,

$r, k$  link specific constants.

Skabardonis et al. (56) stated that the standard BPR curve underestimated speeds at v/c ratios between 0.8 to 1.0 and overestimated speeds when the demand exceeds capacity. They recommended updated BPR type curves, for both freeways and signalized arterials, which are flatter than the standard BPR curve for v/c ratio less than 0.7, and drops much faster when v/c ratio approaches 1.0. However, in a follow up study, Dowling et al. (57) stated that the updated curve significantly increases the convergence time to equilibrium solutions in the traffic assignment process.

### 2.2.2 Link Travel Time Functions under Traffic Control

According to Berka (13), as long as traffic is not over congested, cruise time is flow independent. The estimation of intersection delays is much more complicated. A comprehensive review on intersection delay estimation is presented in Nagui Roupail et al. (42). One of the first delay functions at intersections was derived by Beckman (2) with the assumption of a binomial arrival pattern, which is shown below:

$$d = \frac{C - g}{C(1 - f/s)} \left[ \frac{Q_0}{f} + \frac{C - g + 1}{2} \right] \quad (2.20)$$

where,

$C$  = cycle length

$g$  = green time

$f$  = traffic flow

$s$  = saturation flow

$Q_0$  = expected overflow queue from the previous cycle.

Because it is very difficult to get the exact form of  $Q_0$ , a large number of approximate delay estimation models were developed after Beckman's formulation. Early works were all based on steady-state stochastic delay models, which require strong distribution assumptions on arrival patterns. The fundamental and still extensively used delay estimation model was developed by Webster (11). As for most delay functions, it is composed of two terms, the uniform delay and the random delay. Numerous other early steady-state delay estimation models were also developed, which were often different from Webster's approach by the way how overflow queues were estimated.

However, when the network is over saturated, or in other words when the v/c ratio is greater than 1.0, delays estimated from steady-state stochastic models will quickly increase to a very large value. According to Berka (13), such delay functions can not be applied in a route choice model where overflow delay may occur even if the network is under saturated. Akcelik (43) developed a model that can be used in over saturated

situations. Based on extensive field studies, Reilly et al. (44), modified Akcelik's formula, and Reilly's equation was further modified by Roess et al. (45), and the improved model is applied by the 1997 HCM (46).

Another limitation of steady-state stochastic models is that they do not reflect the coordination of adjacent intersections. None of the above mentioned studies incorporated offsets in their models. In a transportation network, with coordinated signals, offsets are critical decision variables. Network-wide signal setting problems are characterized by the optimization of offsets. To optimize signal coordination, offsets must be incorporated into the link travel time estimation function as independent variables. These types of functions are also known as delay-offset functions. The only closed form delay-offset function was provided by Gartner (38).

One of the most important contributions to the modeling of link travel time estimations with turning movement delays was done by Berka et al. (13). For the estimation of cruise time, Berka et al. obtained a formula by regression from the measurement data of the 1985 HCM. For the estimation of intersection delays, the models were classified by roadway and intersection types. The roadway types considered are arterials, collectors, freeways and tollway facilities. They further divided the arterials and collectors into signalized intersections, major/minor priority intersections and all-way-stop intersections. The models for arterials and collectors are the most complicated ones, because these types of roads are located in urban areas, and their control, geometric, and flow characteristics are more complicated than other types. Arterial and collector intersections were classified into 12 categories according to the intersection control, the intersection layout and the intersection geometry. Their analysis was based on a lane

group basis, except for the left turn lane that was analyzed separately, which is consistent with the 1997 HCM (46). The intersection delay analysis consists of four modules: lane flow estimation, saturation flow analysis, signal timing procedure and delay function estimation. These modules are mutually dependent, requiring an iterative procedure to obtain consistent results. Compared with BPR curve based travel time estimation method, Berka et al.'s procedure are more appropriate for controlled facilities. However, one important traffic flow factor, the progression, was ignored in their procedure.

### **2.2.3 Signal Timing Optimization**

One of the critical elements of the procedure proposed in this study is the signal timing optimization. By its nature, this is a rather complicated problem. For isolated intersections, the fundamental work has been done by Webster (3). Because of its simple form, it is widely used in transportation network optimization models. However, the discrepancy between the global optimal objectives of transportation network optimization problems and the non-global nature of isolated intersection signal setting approach requires a different signal optimization approach than Webster's. The network-oriented signal setting model was first introduced by Little (47), using the bandwidth maximization method. However, Little's method, and all other similar maximum-bandwidth methods thereafter, did not take into account traffic flows, which are widely accepted as one of the main factors affecting signal optimization in networks. In the mid-60's, flow-dependent signal optimization packages were developed in the U.S., including SICTRID (48) and SIGOP (49). However, these packages failed to consider loop constraints, which require offsets and greens on a loop to add up to cycle length

multiplied by an integer. In Britain, combination methods (51) were developed by the Road Research Laboratory to calculate optimal offsets for series-parallel networks. Later, the Road Research Laboratory developed another signal optimization method TRANSYT. Both the combination methods and the TRANSYT used the critical intersection approach to calculate the cycle length. These methods calculated the cycle length of the most congested intersection in a network, and then made it the cycle length of all the intersections in the network, which may not be optimal for a network situation. Simultaneous optimization of all decision variables: green splits, cycle length and offsets was first introduced by Gartner (50) in 1975. He used a mixed integer linear programming model to optimize all variables. The objective function of Gartner's model needs to be linearized, that increases both the number of variables and the number of constraints, and makes it very difficult to be applied to real size transportation networks.

Some of the existing commercial signal optimization software is discussed next. TRANSYT-7F is the most popular one for networks, while PASSERII-90 is popular for signal optimization for arterials. TRANSYT-7F was developed as part of the national signal timing optimization project (NSTOP). It is a macroscopic simulation software that simulates traffic in small time increments (39). The quality of progression is reflected in TRANSYT-7F by a platoon dispersion model that is capable of being used to simulate traffic dispersion realistically. TRANSYT-7F uses Webster's method to estimate delays which consists of three parts, uniform delay, random delay and an empirically adjustment factor. The TRANSYT-7F input includes network configuration data, timing data, saturation flow data, speed data and volume data. The output of TRANSYT-7F includes cycle lengths, phase lengths, intersection delays, total travel time, average speeds, fuel

consumption etc. For a given cycle length, TRANSYT-7F can be used to optimize phase lengths and offsets. The program can evaluate a range of cycle lengths and select the best one. The objective function used in the optimization process is the performance index (PI), which is defined by the users. The most commonly used PI is a weighted combination of stops and delays, i.e.:  $PI = \text{delay} + "k" * \text{stops}$ , where  $k$  is the stop penalty. Another well known software is PASSER II-90, which was developed by Texas Transportation Institute of the Texas A&M University System. PASSER II-90 is a computer program that can assist traffic engineers in analyzing both individual signalized intersections and progression operations along an arterial street (36). PASSER II-90 can be used to optimize progression signal timing. It can optimize up to 20 intersections along the arterial. PASSER II-90 can examine a range of cycle lengths and select the one that provides the best progression. It uses the Webster's method to calculate cycle lengths and green splits. The input of PASSER II-90 includes network configuration data, speed data, volume data, timing data and control data. The output of PASSER II-90 includes cycle lengths, efficiency (the average fraction of the cycle used for progression), average speed through system, total travel delay, total fuel consumption, intersection  $v/c$  ratios, phase time, intersection delays, and level of service. In the optimization process, the efficiency is used as the objective function.



## 2.3 The Lower Level Problem (Traffic Assignment Problem)

### 2.3.1 The Variational Inequality Based Formulation

In 1980, Dafermos first pointed out that the equilibrium conditions are equivalent to a variational inequality problem (VIP) formulation. Dafermos' formulation (23) is described below:

Find  $(x^*, T^*) \in \Omega$ , such that:

$$c(x^*)(x - x^*) - \theta(T^*)(T - T^*) \geq 0 \quad \forall (x, T \in \Omega) \quad (2.21)$$

$$\Omega = \left\{ (x, T): \sum_{p \in P_{ij}} f_p = T_{ij} \quad \forall (i, j); x_a = \sum_p \delta_{ap} f_p; f \geq 0; T \geq 0 \right\} \quad (2.22)$$

where:

$x = (\dots, x_a, \dots)$  denotes link flows,

$f = (\dots, f_p, \dots)$  denotes path flows,

$\delta_{ap} = 1$  if link  $a$  is on path  $p$ ,

$\delta_{ap} = 0$  otherwise,

$c(x) = (\dots, c_a(x), \dots)$  where  $c_a(x)$  denotes average travel cost on link  $a$ ,

$T = (\dots, T_{ij}, \dots)$  where  $T_{ij}$  denotes O-D flow for O-D pair  $(i, j)$ ,

$\theta = (\dots, \theta_{ij}(T), \dots)$  where  $\theta_{ij}(T)$  is the inverse travel demand function for O-D pair  $(i, j)$ .

Existence conditions for this VIP are that  $c(x)$  and  $-\theta(T)$  must be continuous and  $T(u)$  ( $u$  is the user equilibrium travel time) are bounded from above. Uniqueness conditions are that  $c(x)$  and  $-\theta(T)$  are strictly monotone increasing. The variational inequality mathematical formulation is more general as it describes the UE conditions directly, and it applies to both symmetric and asymmetric cases.

### 2.3.2 The Mathematical Programming Formulation (The Symmetric Traffic Assignment Problem)

If link interactions are symmetric, the traffic assignment problem can be formulated as a mathematical programming problem (12). However, the mathematical programming formulation is not intuitive to the UE conditions, and it can only be applied to symmetric link interaction case only. For the user equilibrium conditions, Beckman et al.'s formulations is as follows:

$$\text{Min. } z = \sum_{a=1}^n \int_0^{x_a} t_a(t) dt \quad (2.23)$$

subject to:

$$\sum_k f_k^{rs} = q^{rs} \quad \forall k, r, s \quad (2.24)$$

$$f_k^{rs} \geq 0 \quad \forall k, r, s \quad (2.25)$$

$$x_a = \sum_r \sum_s \sum_k f_k^{rs} \delta_{ak} \quad (2.26)$$

where,

$x_a$  is the flow on link  $a$ ,

$x = (\dots, x_a, \dots)$  is the link flow vector,

$f_k^{rs}$  is the flow on path  $k$  of O-D pair  $rs$ ,

$q^{rs}$  is the travel demand between O-D pair  $rs$ ,

$t_a(x)$  is the travel time function (performance function) of link  $a$ ,

$\delta_{ak}^{rs} = 1$  if path  $k$  of O-D pair  $rs$  is on link  $a$ , and 0 otherwise.

The solution to the above mathematical problem produces an equilibrium traffic flow pattern.

For the system optimal formulation, the objective function is to minimize the total travel time that is presented below.

$$\min z(x) = \sum_i x_i t_i(x_i) \quad (2.27)$$

subject to (2.24)-(2.26).

Both the UE and the SO formulations can be solved by the Frank-Wolfe algorithm, which was originally proposed by LeBanc et al. (2). According to Sheffi (5), solving the SO formulation is equivalent to solving an UE program in which the cost functions  $t_i(x_i)$  are replaced by the corresponding marginal cost functions  $\tilde{t}_i(x_i)$ .

$$\tilde{t}_i(x_i) = t_i(x_i) + x_i \frac{dt_i(x_i)}{dx_i} \quad (2.28)$$

## **2.4 Solution Algorithms for the Lower Level Problem (The Traffic Assignment Problem)**

### **2.4.1 Solution Algorithms for the Symmetric Traffic Assignment Problems**

In the following sections, two algorithms that are used to solve the symmetric traffic assignment problem are presented. The first one is the Frank-Wolfe algorithm (7), and the second one is a path based gradient projection (GP) algorithm.

Frank-Wolfe algorithm is the most commonly used algorithm in solving symmetric traffic assignment problems. Frank and Wolfe (7) originally suggested the algorithm, and it is also known as the convex combination method. The Frank-Wolfe algorithm is a feasible descent method that is based on a linear approximation of the objective function at each iteration. The descent direction is found by optimizing a linear approximation of the objective function. The move size along the descent direction is found by minimizing the approximated objective function. The Frank-Wolfe algorithm has been widely used in traffic assignment problems because of the equivalence between the descent direction finding step and the all-or-nothing assignment. The all-or-nothing assignment requires repeated applications of one-node-to-all-nodes shortest path routine. This shortest path routine is the main computational requirement of Frank-Wolfe algorithm.

The Gradient Projection (GP) algorithm is a path-based algorithm. Path-based algorithms have not drawn enough attention by transportation researchers because the algorithms require very large computer memory. The basic idea behind the GP algorithm is that for any feasible solution a better solution can be found by moving along the negative gradient direction. The negative gradient direction is calculated with respect to the flows on the non-shortest paths, and a move size is found by using the second

derivatives with respect to these path-flow variables. Jayakrishnan et al. (28) have presented an application of the GP algorithm. Their research suggests that the memory problems of the GP algorithm can be addressed effectively by existing computer hardware and software. They have also demonstrated that the computational performance of the GP over the Frank-Wolfe is substantial.

#### 2.4.2 Solution Algorithms for Asymmetric Traffic Assignment Problems

Given a link flow vector  $x = (x_1, \dots, x_n)$  and the link travel time vector  $t(x) = (t_1(x), \dots, t_n(x))$ , the asymmetric traffic assignment problem can be formulated as a variational inequality problem (VIP) as follows:

$$\text{Find } x^* \in X \text{ such that } t(x^*)(y - x^*) \geq 0, \forall y \in X$$

To solve asymmetric UE traffic assignment problems, a sequence of symmetric problems must be defined to approximate the asymmetric problems. Friesz (8) summarized the available solution algorithms and grouped them into three categories:

##### 1. Linearization methods

In a linearization algorithm, at each iteration  $t(\cdot)$  is approximated by a linear approximation  $t^{(k)}(x)$ .

$$t^{(k)}(x) = t(x^{(k)}) + A(x^{(k)})(x - x^{(k)}) \quad (2.29)$$

Then the VIP is solved:  $t^{(k)}(x^*) \cdot (y - x^*) \geq 0, \forall y \in X$  to get  $x^{(k+1)}$  until certain termination criterion is satisfied. When  $A(x^{(k)})$  is chosen as a symmetric positive definite matrix, the algorithm is called the projection method (23).

## 2. Diagonalization methods (6,15)

In the diagonalization algorithm (also known as nonlinear Jacobi methods), at each iteration a diagonalization of function  $t(\cdot)$  is performed to obtain:

$$t^{(k)}(x, x^{(k)}) = [\dots, t_i^{(k)}(x_i, x_j = x_j^{(k)}), \dots] \quad (2.30)$$

Then the VIP is solved:  $t^{(k)}(x^*) \cdot (y - x^*) \geq 0 \quad \forall y \in X$  to get  $x^{(k+1)}$  until certain termination criterion is satisfied.

Sheffi (5) proposed a streamlined version of the diagonalization algorithm by performing only one iteration of the symmetric UE sub-problem. Mahmassani and Mouskos (15) conformed that the sub-problem need only be solved approximately, by performing only a few Frank-Wolfe iterations from one to four. They suggested that for each problem trial tests should be conducted to determine the optimal number of iterations.

## 3. Simplicial decomposition methods (22)

In the simplicial decomposition algorithm, the feasible set is represented by extreme points that are updated at each iteration. These extreme points form a convex simplified feasible set that makes the problem easier to solve.

## 2.5 Search Procedures of the Upper Level Problems

Maganati and Wong (14) summarized the solution methodologies for discrete NDP. The search strategies can be grouped into two categories, exact search strategies and heuristic search strategies. The most commonly used exact search method of solving the discrete NDP is the well-known branch and bound technique of integer programming. One of the first studies conducted in this area is the work by LeBlanc (1). He formulated the budget constrained discrete equilibrium NDP as program (2.12)-(2.15), and proposed a branch and bound solution algorithm with SO results as the lower bound. The branch and bound search procedure was also adapted by Hoang (19) and Dionne and Florian (16).

Heuristic search strategies can be divided into two categories: informed and uninformed. The informed search uses information gathered from previous states to guide the search of the next state. The uninformed search proceeds in a way with a predetermined strategy that is independent of the intermediate information from the previous states. The informed strategy is more interesting, because the uninformed one is rather inefficient for large-scale problems. Recent advances in heuristic search strategies of solving large-scale combinatorial problems can be classified into three groups: the TABU search, the simulated annealing and the neural network methods. The next two sections present the principal characteristics of the TABU search and the simulated annealing methods.

### 2.5.1 TABU Search

TABU search was developed by Glover (24-26). The first application of TABU search to solve the UE single class discrete UTNDP was developed by Mouskos (3). The principle elements of TABU search are the followings:

- **TABU lists:** TABU lists contain a set of moves that are not permitted to be undertaken during a certain number of iterations during the search. The primary purpose of these lists is to move the search away from the current search space and reduce the risk of cycling.
- **Heuristic evaluation functions:** The heuristic evaluation function is used to evaluate all available moves and the move where the best value is selected to move from one solution state to another.
- **Aspiration level:** The aspiration level is used to override the TABU status of a move if its evaluation function reaches a certain value (aspiration level).
- **Strategic oscillation:** Strategic oscillation is often used to search the space around the boundaries of the constraints. It serves as a sensitivity analysis tool to the search.
- **Intermediate memory function:** Intermediate memory function rewards good moves to intensify the search around good solutions.
- **Long term memory function:** Long term memory function is used to diversify the search into another place of the solution space.
- **Dominant and deficient moves:** A move is called a dominant move if when a TABU condition prevents this move, it also prevents a set of associated moves. A move is called a deficient move if it provides no possibility for an improved solution.



TABU search has been applied in different types of problems, such as the job scheduling problem, the computer channel balancing problem, and the travel salesmen problem. Mouskos (3) successfully implemented TABU search in a single user class discrete transportation equilibrium network design problem. He used five small experimental networks to test the algorithm, where the optimal solutions were obtained in less than 500 iterations. He also tested his method on three medium size networks, where good solutions were also obtained.

### 2.5.2 Simulated Annealing Procedure

The basic search strategy follows the Metropolis algorithm (32). The Metropolis algorithm was motivated by an analogy to the physical annealing process of solids. In condensed matter physics, annealing is known as a thermal process for obtaining a low energy state of a solid in a heat bath. If the cooling process is conducted in such a way that at every temperature a thermal equilibrium of the object can be reached, then the material internal energy will be reduced greatly or even reduced to the minimal energy state. A thermal equilibrium is reached at a temperature  $T$  if the probability of being in state  $i$  with energy  $E_i$  is governed by a Boltzman distribution:

$$P(E_i) = \frac{\exp\left(-\frac{E_i}{k_B T}\right)}{\sum_j \exp\left(-\frac{E_j}{k_B T}\right)} \quad (2.31)$$

where  $k_B$  is the Boltzman constant. The basic idea of this algorithm is modeling the transition from the current state to the next state so that the Boltzman distribution can be achieved. The application of this algorithm in UTNDP requires the identification of three elements: move generation, acceptance criteria and cooling schedule. The move generation mechanism is presented in the previous paragraph. The acceptance criterion is constructed as:

$$P_c\{accept\ j\} = \begin{cases} 1 & \text{if } f(j) \leq f(i) \\ \exp\left(\frac{f(i) - f(j)}{c}\right) & \text{if } f(j) > f(i) \end{cases} \quad (2.32)$$

where

$P_c\{accept\ j\}$  is the acceptance probability of state  $j$ ,

$f(i), f(j)$  is the network-wide total travel time of state  $i$  and  $j$ , respectively,

$c \in R^+$  denotes the control parameter.

The cooling schedule defines the number of transitions generated under a control parameter value and the changing plan of this control parameter. The cooling schedule determines the speed of convergence of the algorithm.

For a combinatorial optimization problem, the objective function plays the same role as energy does for the annealing of the physical system. The control parameter plays the same role as temperature does. The solution process of a combinatorial optimization problem can be viewed as a simulated annealing process, evaluated at decreasing values of the control parameter. Simulated annealing algorithm was applied to combinatorial optimization problems by Kirkpatrick et al. (29). The identification of three elements:

the generation mechanism, the acceptance criteria and the cooling schedule are critical to the application of the simulated annealing in combinatorial problems.

The simulated annealing algorithm has been used in job shop scheduling problems by Matsuo et al. (30). Friesz et al. (9) formulated a continuous NDP with variational inequality constraints and proposed a simulated annealing algorithm to solve it. Their conclusion was that the simulated annealing algorithm was superior to other commonly used algorithms in accuracy, but it was very computationally demanding. Only important problems, which require accurate solutions, justified the use of the simulated annealing algorithm. Zeng (44) used a combined simulated annealing and TABU search algorithm (SA-TABU) in solving a discrete UTNDP. He conducted numerical tests on the same five networks (from 18 to 38 links) used by Mouskos (3). Three sets of tests were performed, the first set used the traditional TABU search method, the second set used simulated annealing method, and the last set used the combined simulated annealing and the TABU search algorithm (SA-TABU). These three methods were also tested on three larger networks (1206, 2022, and 3026 decision variables). The SA-TABU search strategy was found to be an efficient and robust algorithm in providing “good” solutions to the problem. Compared with the conventional simulated annealing procedure, the SA-TABU directed its search faster toward a set of “good” solutions, and was more applicable in solving large scale problems.

## **2.6 Network Representation**

Network representation is important both to the model formulation and the algorithm design. A network needs to be constructed in an appropriate way so that it can represent

all the major features of an operational transportation network. Detailed representation method leads to good quality results, however, it is often at the price of an over complicated network representation which significantly increases the computational burden. For example, to represent the turning movements, additional abstract links should be added for each movement at the intersections. The forward star structure is the most widely used data structure to represent a transportation network. In the following sections, three network representation methods are introduced.

### **2.6.1 The Conventional Network Representation**

In conventional route representation, each intersection is represented by a node, and each road segment is represented as an approach link. For details, see Sheffi (5). Turning movements can not be represented by this method. Travel time in this representation are functions of road segment geometry and traffic flows, they are not defined in terms of turning movement attributes.

### **2.6.2 The Expanded Intersection Representation**

For some transportation network studies, turning movements are very important. For example, in urban areas, the cruise time spent on an approach link is often much less than the delays occurred at intersections. These delays are due to either signal settings or conflicting traffic flows when turning movements are involved. The turning movements in urban signalized networks can not be ignored, and should be represented appropriately.

Under the expanded intersection representation, each turning movement is represented by an abstract link that is called an intersection link. The links connecting

adjacent intersections are called non-intersection links, or regular links. Because of the network expansion, it requires increased computational time and computer memory.

### **2.6.3 Extended Forward Star Structure (EFSS)**

In 1996, Ziliaskopoulos et al. (41) developed a method in a more economical, compact and manageable way to represent networks. His study is an extension to the commonly used forward star structure with a network representation method that can be used to represent intersection movements, the associated delays and movement prohibitions.

## **CHAPTER 3**

### **METHODOLOGY**

In this chapter, the UTNDP is formulated as a bi-level mathematical program. Then the link performance function estimation model is presented, followed by the signal setting model. Next, the UE diagonalization algorithm is presented, which is adopted to solve the asymmetric interactions between link flows in signalized networks. This chapter concludes with a description of the heuristic used to solve the UTNDP bi-level program that employs a combined Simulated Annealing and TABU Search (SA-TABU) strategy.

#### **3.1 Formulation**

The UTNDP is formulated as a typical bi-level programming problem where the upper level problem represents the choices of transportation planners, and the lower level problem represents the choices of the travelers in selecting their routes. The upper level problem includes network configuration and signal setting optimization. Network configuration optimization includes lane designation controls and intersection turning movement controls, which are integrated into the UTNDP model as discrete decision variables. Signal setting optimization includes the cycle time, offsets and greensplits, all of which are continuous variables in the UTNDP. The UTNDP formulation is presented next.

### 3.1.1 A Bi-Level UTNDP Model

A bi-level UTNDP model is constructed to optimize the traffic control strategies as follows:

$$\min_{y,g,\varphi,C} \sum_a t_a(x,y,g,\varphi,C) x_a \quad (3.1)$$

subject to:

$$x_a \leq M y_a \quad \forall a \quad (3.2)$$

$$y_a = (0,1) \quad \forall a \quad (3.3)$$

$$\sum_{a \in F(l)} \varphi_a + \sum_{a \in R(l)} (C - \varphi_a) + \sum_a g_a = n_l C \quad \forall l \in L \quad (3.4)$$

$$g_a + r_a = C \quad \forall a \quad (3.5)$$

$$g_a s_a(x,y) \geq x_a C \quad \forall a \quad (3.6)$$

$$g_a \geq g_{\min} \quad \forall a \quad (3.7)$$

$$C \geq C_{\min} \quad (3.8)$$

$$t(x,y,g,\varphi,C) \cdot (x^1 - x) \geq 0 \quad \forall x^1 \in X \quad (3.9)$$

$$\sum_k f_k^{rs} = q^{rs} \quad \forall k, r, s \quad (3.10)$$

$$f_k^{rs} \geq 0 \quad \forall k, r, s \quad (3.11)$$

$$x_a = \sum_r \sum_s \sum_k f_k^{rs} \delta_{ak}^{rs} \quad \forall a \quad (3.12)$$

where

$x_a$  is the flow on link  $a$ ,

$x = (\dots, x_a, \dots)$  is the link flow vector,

$y_a$  is the network configuration decision variable, unity if link  $a$  is added to the network, and 0 otherwise,

$y = (\dots, y_a, \dots)$  is the network configuration decision variable vector,

$g_a$  is the green split on link  $a$ ,

$g = (\dots, g_a, \dots)$  is the green split vector,

$g_{\min}$  is the minimum green split,

$\varphi_a$  is the offset on link  $a$ , with respect to the upstream intersection,

$\varphi = (\dots, \varphi_a, \dots)$  is the offset vector,

$C$  is the network-wide cycle length,

$C_{\min}$  is the minimum cycle length,

$f_k^{rs}$  is the flow on path  $k$  of O-D pair  $rs$ ,

$q^{rs}$  is the travel demand between O-D pair  $rs$ ,

$t(x, y, g, \varphi, C) = (\dots, t_a(x, y, g, \varphi, C), \dots)$  is the travel time function vector,

$M$  is a large constant,

$\delta_{ak}^{rs} = 1$  if path  $k$  of O-D pair  $rs$  is on link  $a$ , and 0 otherwise,

$l$  is the set of links that form a loop,

$L = \{l\}$  is the set of all the loops,

$F(l)$  is the set of forward links in  $l$ ,

$R(l)$  is the set of backward links in  $l$ ,



$n_l$  is the integer loop constraint multiplier,

$s_a(x, y)$  is the saturation flow rate on link  $a$ .

Program (3.1)-(3.8) represents the upper level problem of an UTNDP. Function (3.1) is the objective function which represents the network-wide total travel time (travel time includes intersection delays hereafter). Constraint (3.2) prevents flows on turning movements that are not allowed. Signal setting related constraints are represented in (3.4)-(3.8) and are explained in detail in section 3.1.4.

Program (3.9)-(3.12) defines the traffic assignment, the lower level problem. The VIP constraint (3.9) defines the user equilibrium (UE) traffic conditions. Constraint (3.10) is the flow conservation constraint, constraint (3.11) is the non-negativity constraint, and constraint (3.12) is the incidence relationship between link flows and path flows. Also, note that link performance functions (link travel time functions)  $t_a(x, y, g, \varphi, C)$  are functions of link flows  $x$ , network configuration variables  $y$ , and signal setting variables  $g$ ,  $\varphi$ , and  $C$ . The travel time on a subject link depends not only on the flow or the link itself, but also on the flows on other links and signal setting variables.

The objective of this UTNDP model is to optimize traffic control strategies so that the UE network-wide total travel time is minimized. At the upper level, transportation planners decide lane designation controls, intersection movement controls and signal setting controls. At the lower level, travelers choose their route individually, so that at the equilibrium state the UE conditions are satisfied. There are three types of decision variables. The upper level decision variables include network configuration variables  $y$  and signal setting variables  $g$ ,  $\varphi$ , and  $C$ . The network configuration variables are used

to represent whether certain turning movements should be prohibited/permitted at some intersections, or whether lane designations should be rearranged and how they should be rearranged. The signal setting variables represent how signal splits and offsets are allocated to each intersection and how long the network-wide cycle length should be. The lower level traffic flow variables  $x$  represent the link flows at the UE state.

### 3.1.2 The Link Performance Function Estimation Model

In previous NDP studies, the BPR type curve was the most commonly used function form of link performance functions. The BPR curve is appropriate for freeway type traffic conditions where the link travel time depends on the flow on the link. However, for over-saturation conditions (i.e. where volume exceeds capacity), even on freeways the BPR type curve does not perform well.

In this UTNDP, because of the introduction of intersection turning movements, it is necessary to distinguish between the delay occurred at intersections and the cruise time on regular links. From hereon, link performance functions refer to both intersection delay functions and cruise time functions. Compared with the cruise time estimation, the intersection delay estimation is computationally more demanding because of the involvement of signal setting variables in the estimation procedure.

As it will be explained in the algorithm section of this chapter (section 3.2), the network configuration variables  $y$  and signal setting variables  $g$ ,  $\phi$ , and  $C$  are updated separately in two consecutive steps at the upper level of the UTNDP in an iterative procedure. When updating  $y$ , variables  $x$ ,  $g$ ,  $\phi$ , and  $C$  are fixed with their values of the previous iteration;  $y$  and  $x$  are fixed when updating  $g$ ,  $\phi$ , and  $C$ . In this UTNDP

formulation, the intersection delay function used in the 1994 HCM is chosen as the link performance function for updating  $y$ . The third term in the 1997 HCM delay formula is not used in this study because this UTNDP is only applicable to undersaturated conditions with no initial queues.

$$t_a(x, y, g, C) = d_{a1}DF + d_{a2} \quad (3.13)$$

$$d_{a1} = 0.38[1 - g_a / C]^2 / \{1 - (g_a / C)[\text{Min}(X_a, 1.0)]\} \quad (3.14)$$

$$d_{a2} = 173X_a^2 \{(X_a - 1) + [(X_a - 1)^2 + mX_a / c_a]^{0.5}\} \quad (3.15)$$

where:

$d_{a1}$  uniform delay on lane group  $a$  (sec/vehicle),

$d_{a2}$  overflow delay on lane group  $a$  (sec/vehicle),

$DF$  delay adjustment factor for quality of progression and control type,

$X_a$   $x_a / s_a$  ratio for lane group  $a$ ,

$s_a$  saturation flow rate of lane group  $a$ , vph,

$m$  an overflow delay calibration term representing the effect of arrival type and degree of platoon,

All other variables are the same as before.

To update signal setting variables, a link performance function that includes all  $g$ ,  $\phi$ , and  $C$  as its independent signal setting variables is needed. The only function that includes offset  $\phi$  as independent variables so far was proposed by Gartner (38).

Gartner's formulation is used in updating  $g$ ,  $\varphi$ , and  $C$  in this UTNDP model. It is presented as follows:

$$t_a(x, y, g, \varphi, C) = Z_a(C, g_a, \varphi_a) + Q_a(C, g_a) \quad (3.16)$$

where,

$Z_a$ : delay time incurred by a uniform platoon at the downstream signal of link  $a$ ,

$$Z_a = (t_{0a} - \varphi_a)^2 / 2pC(1 - x_a / ps_a) \quad (3.17)$$

$t_{0a}$ : travel time at zero volume on link  $a$ ,

$p$ : platoon length (in fraction of cycle time)

$Q_a$ : random delay of this platoon at the downstream signal of link  $a$ ,

$$Q_a = (x_a / k_a) / k_a (1 - x_a / k_a)^2 + [1.25 \left( \frac{1 - x_a / k_a}{k_a C} \right)^2 + 2.25 (x_a / k_a)^2 \left( \frac{1 - x_a / k_a}{k_a C} \right) + 0.008 (x_a / k_a)^3] \quad (3.18)$$

$$k_a = g_a s_a / C \quad (3.19)$$

The estimation of the cruise time follows the method proposed by Greenshields (52). The linear model Greenshields proposed to estimate the average running speed on a link is:

$$v_a = v_{af} - \frac{v_{af}}{D_{aj}} D_a \quad (3.20)$$

where,

$v_a$  is the average running speed on link  $a$  (mph),

$v_{af}$  is the free flow speed on link  $a$  (mph),

$D_a$  is the density on link  $a$  (vpmpl),  $D_a = \frac{x_a}{v_a}$ ,

$D_{aj}$  is the jam density (vpmpl), the density at which all movements stop.

Assuming that the average length of a vehicle to be 15 feet and the gap between two vehicles under jam conditions is 2 feet, the jam density is then 311 (vpmpl). The average running speed can be calculated as:

$$v_a = \frac{v_{af}}{2} + \sqrt{v_{af} \left( \frac{v_{af}}{4} - \frac{x_a}{D_{aj}} \right)} \quad (3.21)$$

The cruise time is then estimated as:

$$t_a(x_a, v_{af}) = \frac{3600 \times L_a}{v_a} \quad (3.22)$$

Here,  $L_a$  is the link length (miles).

The following sections address how lane group based intersection delays are converted to movement based intersection delays.

### 3.1.3 The Conversion of Lane Group Based Delays to Movement Based Delays

The optimization of intersection movement controls requires a movement based intersection delay estimation procedure. However, the 1994 HCM procedure (3.13)-(3.15) is lane group based. To mitigate this discrepancy, ‘through-vehicle-equivalent’ factors are used to convert the lane group based delays to movement-based delays.

According to 1994 HCM, the left turn ‘through-vehicle-equivalent’ factor

$$\text{is } E_L = \frac{1900}{1400 - x_o}, \text{ the right turn ‘through-vehicle-equivalent’ factor is } E_R = \frac{1900}{1700}.$$

Variable  $x_o$  represents the opposite link flow. If the left turn, through, and right turn movements are all in one lane group, then:

$$p_{ar}d_{ar} + p_{al}d_{al} + (1 - p_{ar} - p_{al})d_{at} = d_a \quad (3.23)$$

where,

$d_a$  is the average intersection delay of lane group  $a$ ,

$d_{at}, d_{al}, d_{ar}$  are the average through, left turn and right turn intersection delays

respectively,  $d_{al} = E_L d_{at}$ ,  $d_{ar} = E_R d_{at}$ ,

$p_{ar}, p_{al}$  are the percentages of right turn and left turn traffic in lane group  $a$ .

From (3.23), the following equations can be derived:

$$d_{at} = \frac{d_a}{1 + \frac{x_o + 500}{1400 - x_o} p_{al} + \frac{3}{17} p_{ar}} \quad (3.24)$$

$$d_{at} = \frac{1900}{1400 - x_o} d_{at} \quad (3.25)$$

$$d_{ar} = \frac{1900}{1700} d_{at} \quad (3.26)$$

### 3.1.4 The Signal Setting Model

The objective of this UTNDP model is to minimize network-wide total travel time. This network-wide optimization nature requires the signal setting optimization, a critical component of the UTNDP, to be orientated in a way that network-wide signal settings are optimized rather than the optimization of signals at isolated intersections.

In an signalized transportation network, the signal efficiency not only depends on the cycle length and the green splits at individual intersections, but also depends on the coordination of signals. This coordination is reflected as offsets between adjacent intersections. Gartner (50) proposed a model to optimize cycle length, green splits, and offsets simultaneously. His model, whose objective function and constraints are presented in (3.1) and (3.4)-(3.8), is used in the UTNDP model to optimize signal settings.

Equation (3.4) is the loop constraint, where the sum of the offsets, and the corresponding green splits around any loop of the network are set to be equal to an integer multiple of the cycle time. Equation (3.5) is the cycle constraint, where for any link  $a$ , the green and red split on it should add up to one cycle length. Constraint (3.6) is the capacity constraint for any approach of an intersection. Constraints (3.7) and (3.8) are the minimum green and minimum cycle length constraints, respectively.

This model is a nonlinear mixed integer programming model, which is computationally difficult to solve even for small to medium size networks. To reduce the computational complexity, the model can be relaxed in two ways. One way, as proposed by Cantarella (35), is to separate the optimization of offsets from other variables, so that the size of the model can be reduced significantly. The other way is to relax the loop constraint that causes the complexity of the model because of the existence of the integer loop constraint multipliers. In an UTNDP, because the signal setting model needs to be solved in each UTNDP iteration, and because both the signal decision variables and the signal related constraints can easily increase to a size beyond any reasonable computational capabilities, it is often unavoidable to relax the signal setting model to a scale that is solvable. In this dissertation, only a few major loop constraint and the related offsets are left in the model, and all the other offset variables are set, using the loop constraint equations.

### 3.2 Solution Algorithms

The UTNDP is a large-scale bi-level nonlinear problem with both discrete and continuous decision variables. Since it is very difficult to obtain an exact optimal solution for such a problem, a heuristic search procedure is used to find near optimal solutions. The heuristic search uses information gathered from previous solution states to guide the search of the upper level discrete network configuration decision variables  $y$ .

The solution of the lower level asymmetric UE traffic assignment problem requires the solution of a sequence of approximately defined symmetric problems. The



Frank-Wolfe algorithm is used to solve the symmetric UE traffic assignment problem. The approximation is achieved by the diagonalization method (5).

### 3.2.1 The Heuristic Search Strategy

In this section, a solution procedure for the UTNDP model is presented as follows:

#### Step 0: Initialization

Initialize network configuration variables  $\gamma$ , signal setting variables  $g, \varphi$  and  $C$ , and saturation flow rates  $s$ ;

Solve an all-or-nothing traffic assignment, find initial link flows  $x_0$ .

#### Step 1: Update Upper Level Decision Variables $\gamma$ .

Use the SA-TABU search procedure to update discrete network configuration variables  $\gamma$  (represent lane designations and intersection movement controls).

##### Step 1.1 Update Heuristic Evaluation Function (HEF) Values

Update the HEF values for each link, using the current solution information, historical contribution information, and a random factor.

##### Step 1.2 Sort the HEF values in descending order.

##### Step 1.3 Update $\gamma$ with the highest HEF value.

#### Step 2: Update Saturation Flow Rates

#### Step 3: Solve the Signal Setting Sub-Problem

#### Step 4: Solve the Lower level Asymmetric UE Traffic Assignment

Use a streamlined diagonalization method to solve the UE asymmetric traffic assignment problem.

##### Step 4.1 Diagonalization

For any link  $a$ , fix all arguments of  $t_a(\cdot)$  other than  $x_a$ , i.e.:

$$\tilde{t}_a^n(x_a) = t_a(x_1^n, \dots, x_{a-1}^n, x_a, \dots, x_{a+1}^n, \dots, x_A^n)$$

This reduces the problem to a symmetric UE traffic assignment problem.

Step 4.2 Solve the symmetric UE traffic assignment problem

Use the Frank-Wolfe algorithm with modified link performance functions to obtain link flows  $x$ . (For detail see section 3.2.4)

Step 4.3 Convergence test

If convergence criteria are met, proceed to the next step. Otherwise set  $n=n+1$ , go to step 4.1.

Step 5: Update Historical Contribution Values (HISCON)

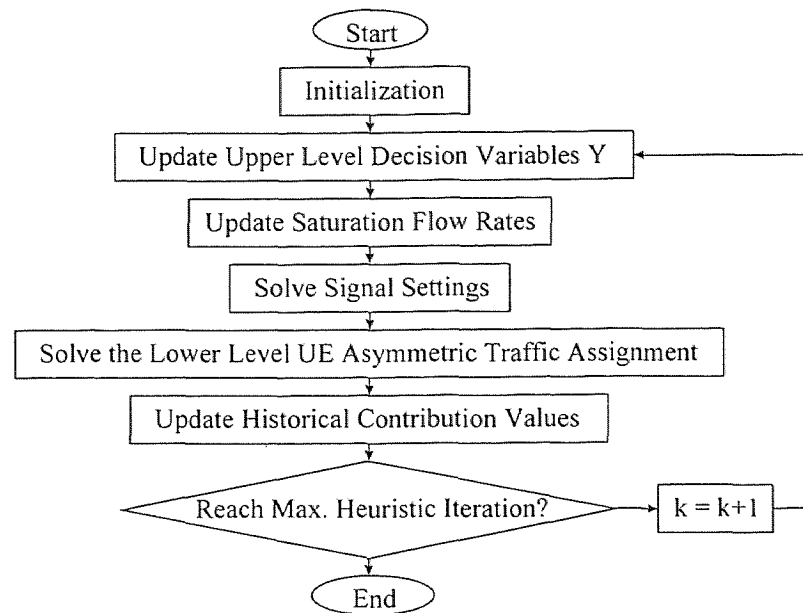
Calculate the difference between the current total travel time and the total travel time of the previous state. Use this difference to update the historical contribution values.

Step 6: Heuristic Search Termination Test

If the heuristic search reaches its preset maximum iteration number, stop.

Otherwise, set  $k=k+1$ , go to step 1.

The above procedure is depicted in the following flow chart (Figure 3.1):



**Figure 3.1** A General Solution Flow Chart of the UTNDP Model

The ‘Solve Signal Settings’ step is performed by using a nonlinear programming package developed by Dow (53). The package is coded in FORTRAN and embedded into the UTNDP program by modifying and connecting the input file with the output of the UE traffic assignment step. The signal setting step has been discussed in detail in section 3.1.4; all other major steps, the ‘Update Upper Level Decision Variables’, the ‘Update Historical Contribution Values’, and the ‘Heuristic Search Termination Test’ steps are discussed in the following sections.

### 3.2.2 Main Heuristic Steps

This section presents the main steps of the heuristic search procedure used to solve the UTNDP. One of the most commonly used search strategies in combinatorial optimization problems is the simulated annealing procedure. The original simulated

annealing is conservative because the decreasing rate of the move acceptance probability is set to a very small value in order to reach an ‘annealing’ state. Such a procedure is not suitable for a large-scale NDP because of the prohibitive computational demand. By introducing heuristic information into the move generation step, the simulated annealing procedure becomes much more effective. However, this efficiency is achieved at the price of a higher risk of repeated moves toward the state of high HEF values. Zeng (54) proposed a combined Simulated Annealing/TABU search strategy (SA-TABU) to solve an NDP by introducing TABU lists into the move generation step. The use of TABU lists prevents the search procedure from repeating favorite moves by putting the most recent moves into TABU lists. The mechanism of a SA-TABU procedure consists of three major elements: the HEF, the move generation, and the basic search strategy. This research follows the SA-TABU procedure to update the upper level network configuration variables (lane designation variables and intersection movement control variables). The structure of the HEF and the generation of a move have been modified from the original version of HEF suggested by Zeng (54) to better fit the requirements of the UTNDP.

As proposed by Zeng (54), the HEF in this dissertation still has three components: the link heuristic value, the historical contribution factor, and the random factor. The form of the HEF is presented below in equation 3.27.

$$HEF_i = a \times (V_i / C_i) + b \times HISCON_i + c \times RAND(0,1) \quad (3.27)$$

where,

$V_i / C_i$  is the v/c ratio on link  $i$

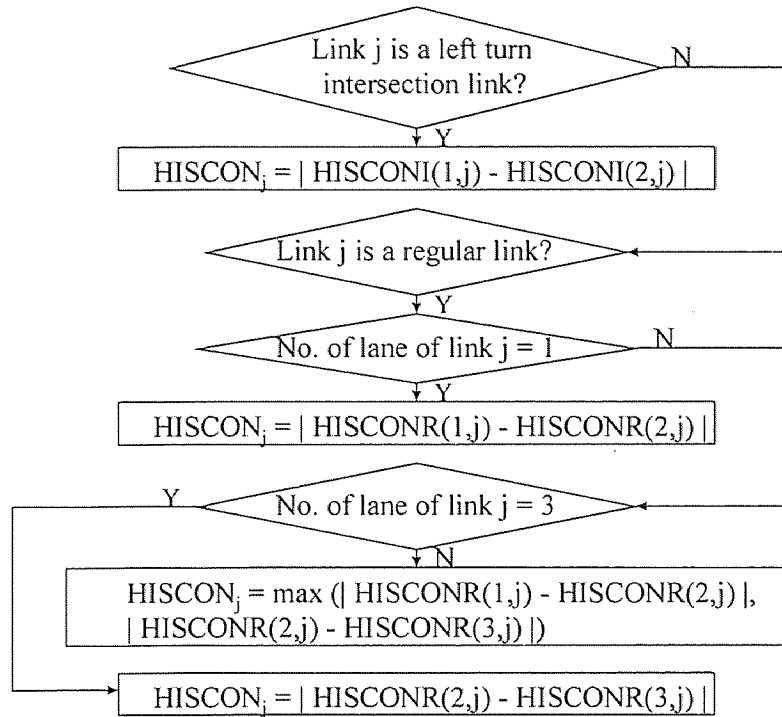
$HISCON_i$  is the historical contribution of link  $i$  at current state,

$RAND(0,1)$  is a random value between 0 and 1,

$a, b$  and  $c$  are problem specific constants.

The historical contribution factor is calculated from the difference between the network-wide total travel times of the current solution state and the previous solution state. The historical contribution of a state of an intersection/regular link is represented by 2-dimension arrays  $HISCONI(i,j)$  and  $HISCONR(i,j)$ , respectively. Here,  $j$  represents the link number, and  $i$  represents the possible link state. For intersection links,  $i$  could be 1 or 2, representing the prohibition ( $y = 0$ ) and the permission ( $y = 1$ ) of a turning movement. For regular links,  $i$  could be 1, 2 or 3, representing the number of lanes on each direction. The historical contribution of link  $j$  is estimated as follows (see Figure 3.2).

A move is defined as a change from the current solution state to a new solution state. Each solution state represents a set of fixed network configurations, which include lane designations and intersection movement controls. The change of any of these network configuration variables leads to a change to a new state. The possible states of intersection movement control variables are either 0 or 1. For an intersection turning movement, the change of  $y$  from 0 to 1 or vice versa represents the change of the state. Since the network in an UTNDP is assumed to be a 4-lane network (two lanes in each direction), the possible values for lane designation variables are 1, 2, and 3, representing the number of lanes in each direction. The case of one-way streets (4 lanes in one direction) is beyond the scope of this study because it introduces another complexity into



**Figure 3.2** Historical Contribution Estimation Flow Chart

the problem. Similar to the intersection movement control, the change of  $y$  values of lane designation variables also leads to a change of the state. The moves used in this study are called guided moves. The variable with the worst (highest) HEF value is selected in each UTNDP iteration to change from its current  $y$  value to a new  $y$  value. For lane designation variables, when their values are 2, there are two possible change directions, from 2 to 1 or from 2 to 3. For such a case, the change of the state is always guided in a way that the value of the subject variable changes from 2 to a state with better historical contribution values. The move is conducted only for variables not in the TABU list. After each move is completed, the most recently updated moves are not allowed to be updated again in the next several iterations.

### 3.2.3 Update Saturation Flow Rates

The saturation flow rate estimation is important because both the link performance functions and the capacity constraint (3.6) are saturation flow rate dependent. In the UTNDP, the saturation flow estimation procedure follows the procedure proposed in the 1997 HCM (46). The formula is presented as follows:

$$s = s_0 \times N \times a_w \times a_{HV} \times a_g \times a_p \times a_{bb} \times a_a \times a_{RT} \times a_{LT} \quad (3.28)$$

where,

$s$  saturation flow rate for the subject lane group,

$s_0$  is the ideal saturation flow rate per lane, 1900 pcphgpl is used in this study,

$N$  is the number of lanes in the lane group,

$a_w, a_{HV}, a_g, a_p, a_{bb}, a_a$  are the adjustment factors for lane width, heavy vehicle,

approach grade, blocking effect of buses and area type respectively,

$a_{RT}$  is the adjustment factor for right turns in the lane group,

$a_{LT}$  is the adjustment factor for left turns in the lane group.

Right turn adjustment factor  $f_{RT}$  is estimated using:

$$a_{RT} = 1 - p_{RT} [0.15 + (PEDS / 2100)] [1 - P_{RTA}] \quad (3.29)$$

where,

$p_{RT}$  is the percentage of right turns in the lane group,

$PEDS$  is the pedestrian flow rate, in pedestrians/hour,

$P_{RTA}$  is the proportion of right turns using a protected right turn phase, for permitted right turn phases, its value is set to 0.0 (no protected right-turn phases are used in UTNDP).

The major computational demand in saturation flow rate estimation arises from the estimation of left turn adjustment factor  $a_{LT}$ . In the UTNDP, left turns are assumed to be handled with permitted phasing. The procedure to estimate  $a_{LT}$  is presented as a series of equations ((3.30)-(3.35)) as follow (46):

$$a_{LT} = \frac{f_m + 0.91(N - 1)}{N} \quad (3.30)$$

where,

$a_{LT}$  is the left turn adjustment factor for the subject lane group,

$f_m$  is the left turn adjustment factor for left lane,

$N$  is the number of lanes in the lane group.

$$f_m = \frac{g_f}{g}(1.0) + \frac{g_u}{g}F \quad (3.31)$$

where,

$g_f$  is the average amount of green time before the arrival of the first left turn vehicle on the subject approach,



$g_u$  is the average amount of green time after the arrival of the first left turn vehicle that is not blocked by the clearance of the opposing standing queue,

$g$  is the green split,

$g_q$  is the average amount of green time required for the opposing standing queue to clear the intersection,

$$g_u = g - g_q \text{ if } g_q \geq g_f, \quad g_u = g - g_f \text{ if } g_f \geq g_q.$$

$$F = \frac{1}{1 + P_L(E_L - 1)} \quad (3.32)$$

where,

$P_L$  is the proportion of left turn vehicles in the left lane,

$E_L$  is the through car equivalent,  $E_L = \frac{1900}{1400 - v_o}$ ,

$v_o$  is the opposite through movement flow.

$$P_L = P_{LT} \left[ 1 + \frac{(N-1)g}{g_f + (g_u / E_L) + 4.24} \right] \quad (3.33)$$

where  $P_{LT}$  is the proportion of left turns in lane group.

$$g_f = g e^{-(0.882 LTC^{0.717})} - t_L \quad (3.34)$$

where:

LTC is the left-turns per cycle, computed as  $[V_{LT}C / 3600]$ , vpc,

$V_{LT}$  is the left-turn flow rate in subject lane group, vph,

$t_L$  is the total lost time per phase, default 3 second.

$$g_q = \frac{v_{o/c} q r_o}{0.5 - [v_{o/c} (1 - q r_o) / g_o]} - t_L \quad (3.35)$$

where:

$v_{o/c}$  is the opposite flow rate in vehs/lane/cycle, computed as  $[v_o C / 3600 N_o]$ ,

$v_o$  is the opposite flow rate, in vphg,

$N_o$  is the number of opposite lanes,

$q r_o$  is the queue ratio for opposite flow, computed as  $[1 - R_{po} (g_o / C)]$ ,

$R_{po}$  is the platoon ratio for opposite flow, default 1.0,

$C$  is the cycle length

$g_o$  is the effective green for the opposite flow,

$t_L$  is the total time lost per phase, default 3 seconds.

### 3.2.4 Solve the Lower Level UE Traffic Assignment

The Frank-Wolfe algorithm is used to solve the symmetric UE traffic assignment problem. This algorithm, when applied to the solution of the standard UE traffic assignment problem (fixed travel demand, no link interactions), can be presented as follows (5):

Step 0: Initialization. Perform all-or-nothing assignment based on  $t_i = t_i(0), \forall i$ , yielding  $\{x_i^1\}$ . Set counter  $n:=1$ .

Step 1: Update. Set  $t_i^n = t_i(x_i^n), \forall i$ .

Step 2: Direction finding. Find the shortest paths between each origin and each destination. Perform all-or-nothing assignment based on  $\{t_i^n\}$ . This yields a set of (auxiliary) flows  $\{f_i^n\}$ .

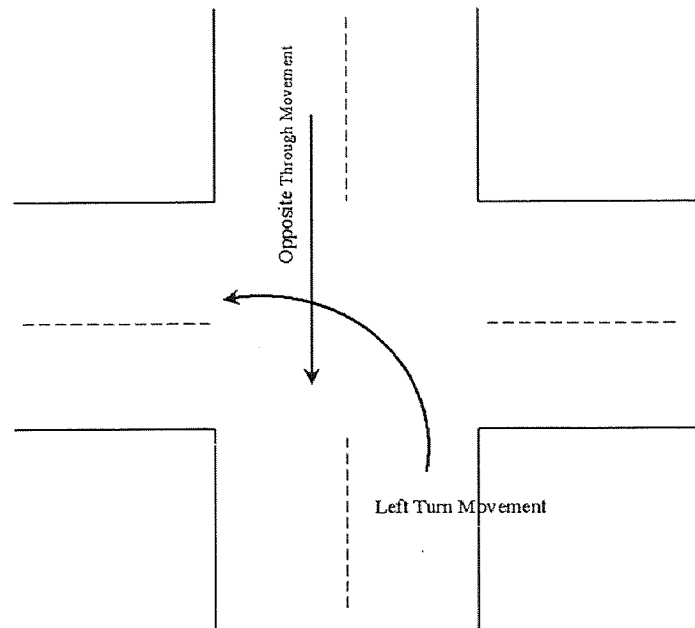
Step 3: Line search. Find  $\alpha_n$  that solves

$$\min_{0 \leq \alpha \leq 1} \sum_{\alpha} \int_0^{x_i^n + \alpha(f_i^n - x_i^n)} t_i(w) dw$$

Step 4: Move. Set  $x_i^{n+1} = x_i^n + \alpha_n(f_i^n - x_i^n), \forall i$

Step 5: Convergence test. If a convergence criterion is met, stop solution; otherwise, set  $n:=n+1$  and go to step 1.

In this UTNDP, the symmetric link performance assumption doesn't hold for intersection links, because of the conflicting intersection movements. The major pair of conflict for a typical 4-leg intersection are the left turn movement and the opposite through movement, or vice versa, as depicted in Figure 3.3 below.



**Figure 3.3** Conflicting Intersection Movements

Under a two phase signal setting plan, when conflicting flows exist, the through movement always has the right of way. The left turn vehicles have to wait for acceptable gaps in the opposite traffic stream to complete their movement. The impact of the opposite left turn vehicles on the delay of the through vehicle is considered as negligible, and the link performance function of the through intersection link is considered as symmetric. For a left turn vehicle, since the opposite through vehicles always have the right of way, the impact of opposite through vehicles is not negligible and the link performance function of the left turn intersection link is asymmetric.

The diagonalization method for asymmetric traffic assignment problems, also known as nonlinear Jacobi method, requires a diagonalization step at each iteration. The

diagonalizing step can be mathematically written as:

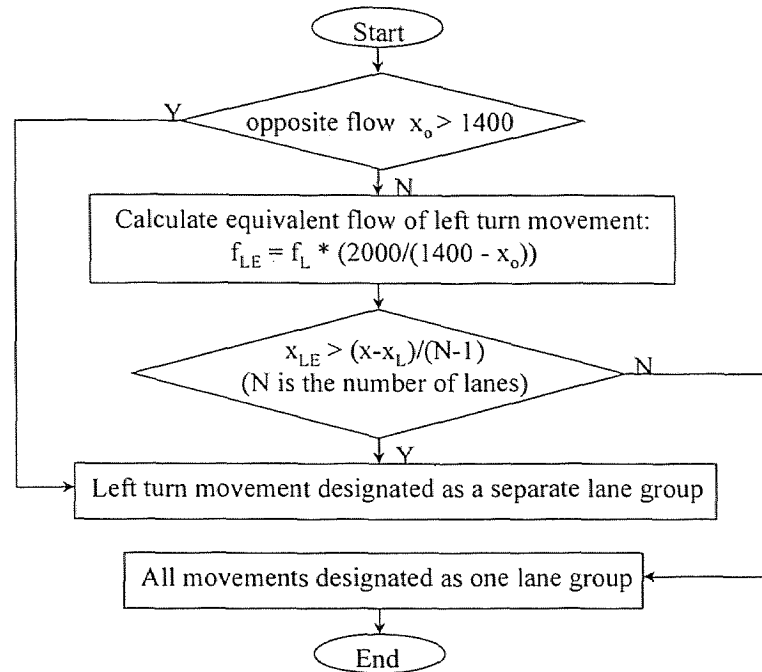
$\tilde{t}_a^n(x_a) = t_a(x_1^n, \dots, x_{a-1}^n, x_a, \dots, x_{a+1}^n, \dots, x_A^n)$ . Or in other words,  $\tilde{t}_a^n(x_a)$  denotes the performance function for links when all arguments of  $t_a(\cdot)$ , other than  $x_a$ , are fixed at their values during the  $n^{\text{th}}$  iteration. With all cross-link effects fixed, the performance functions include only one argument, so at each iteration the problem is reduced to a symmetric UE traffic assignment problem.

In the UTNDP, if link  $a$  is a left turn intersection link, then  $t_a(x_a) = t_a(x_{ot}, x_a)$ , where  $x_{ot}$  is the opposite through flow. For all other types of links, the performance functions are assumed symmetric and only include the subject link flows as independent variables. The 1994 HCM intersection delay estimation procedure, which is used in this UTNDP, does not consider cross-link effects. However,  $t_a(x_{ot}, x_a)$  can be estimated in two steps. First, calculate  $t_a(x_a)$ , and then  $t_a(x_a)$  is approximated to a value close to  $t_a(x_a) = t_a(x_{ot}, x_a)$  by dividing with a weight factor  $a_{LT}$  that is also known as the left turn adjustment factor. The left turn adjustment factor reflects the impact of the opposite through movement on the subject left turn movement by dividing the green of the subject lane group into several critical periods. At each symmetric iteration in the diagonalization step,  $a_{LT}$  is estimated from the flows of the previous solution state, and thus reflects the diagonalization nature of the procedure.

### 3.2.5 Lane Group Designation Procedure

The lane group designation procedure is important to the estimation of link performance functions, because intersection delays are calculated by lane group. Therefore, before the

start of the delay estimation procedure, lane groups must be designated properly. The 1997 HCM (46) lane group designation procedure is shown in the following flow chart (see Figure 3.4).



**Figure 3.4** Lane Group Designation Flow Chart

### 3.2.6 Discussion on the Proposed Solution Procedures

The difficulties of the solution procedures arise from the fact that the UTNDP model is extremely computational demanding. This is due to the following two reasons:

1) Real world transportation networks are often large-scale networks

In most urban areas, the number of streets and intersections is often more than several hundred or even several thousand. To integrate turning movements into the model, one intersection node will need to be expanded to four approaching nodes plus four exiting nodes, and twelve intersection links will need to be added to the network at each

intersection. Therefore, the original network will be expanded to a size much larger than the original network that is already very large.

## 2) The tri-level iterations involved in the model

There is a tri-level iteration involved in the solution algorithm of the model: (1) Solution to the lower level problem. Given a network configuration and the O-D matrix, the asymmetric traffic assignment is solved, (2) Solution to the upper level problem. Given the new traffic flow pattern, a new network configuration is proposed by conducting a heuristic search step, (3) Signal timing optimization. A new signal timing is found based on the network configuration and the new traffic flow pattern.

At the lower level, the diagonalization step has to be performed at each diagonalization iteration, and the shortest path subroutine has to be called repeatedly. At the upper level iteration, given a large size network, the number of upper level decision variables  $y$  is very large. The heuristic search procedure is computationally expensive due to the large number of decision variables  $y$ . The third level of the iteration involved here is the signal timing optimization procedure. Every time the network configuration or flow pattern changes, the signal timing will need to be changed, so the signal timing optimization procedure that is a large-scale nonlinear programming subroutine will be called repeatedly.

The procedure can be expanded to include up to eight phases. In a real world implementation of the UTNDP, this will be desirable, however this will further exacerbate the computational performance of the procedure.

There is a need to develop a more comprehensive travel time function that includes offsets as a variable. A consolidation between Gartner's delay formula and the

1994 HCM delay formula is necessary, in order to have more consistency between the traffic assignment and the signal timing optimization steps.

The cycle length in most urban signalized networks has the same value at all intersections. This approach is used also within the UTNDP. It is noted, however, that this approach constraints the problem to a potential “sub-optimal” solution. A more comprehensive approach would have been to use the cycle length as a variable for each iteration.



## CHAPTER 4

### IMPLEMENTATION OF THE UTNDP SOLUTION HEURISTICS

This chapter presents the computer program implementation of the UTNDP solution algorithm. Programs are coded in FORTRAN 77, and compiled by Fortran PowerStation 4.0 on a PC with Pentium II 350 processor and 64MB memory.

#### 4.1 Overview

The structure of the UTNDP programs is presented in Figure 4.1. There are 34 subroutines in the UTNDP programs, and the three major subroutines are 'UPDATE\_Y', 'SIGNALSET' and 'DIAGONALIZATION'. Subroutine 'UPDATE\_Y' is designed to update the upper level network configuration variables; 'SIGNALSET' is the upper level signal setting optimization subroutine; 'DIAGONALIZATION' is used to solve the lower level asymmetric traffic assignment problem. Subroutines 'UPDATE\_Y' calls the 'UPDATE\_HEF' and the 'UPDATE\_HISCON' subroutines to implement the proposed SA-TABU search strategy. Subroutine 'SIGNALSET' calls a nonlinear programming routine 'NONLINEAR' that is composed of a set of programs developed by Dow (53) (these subroutines are not included in the 34 programs coded by the author of this dissertation). These non-linear optimization programs were originally developed as an independent package, however, several modifications were made to some of the programs so that they could be embedded in the UTNDP program. Among these modified programs, 'p77', the input and nonlinear model construction file, has been significantly changed to fit the requirements of other routines of the UTNDP program. Subroutine 'DIAGONALIZATION' calls 'UE' repeatedly to solve a series of symmetric

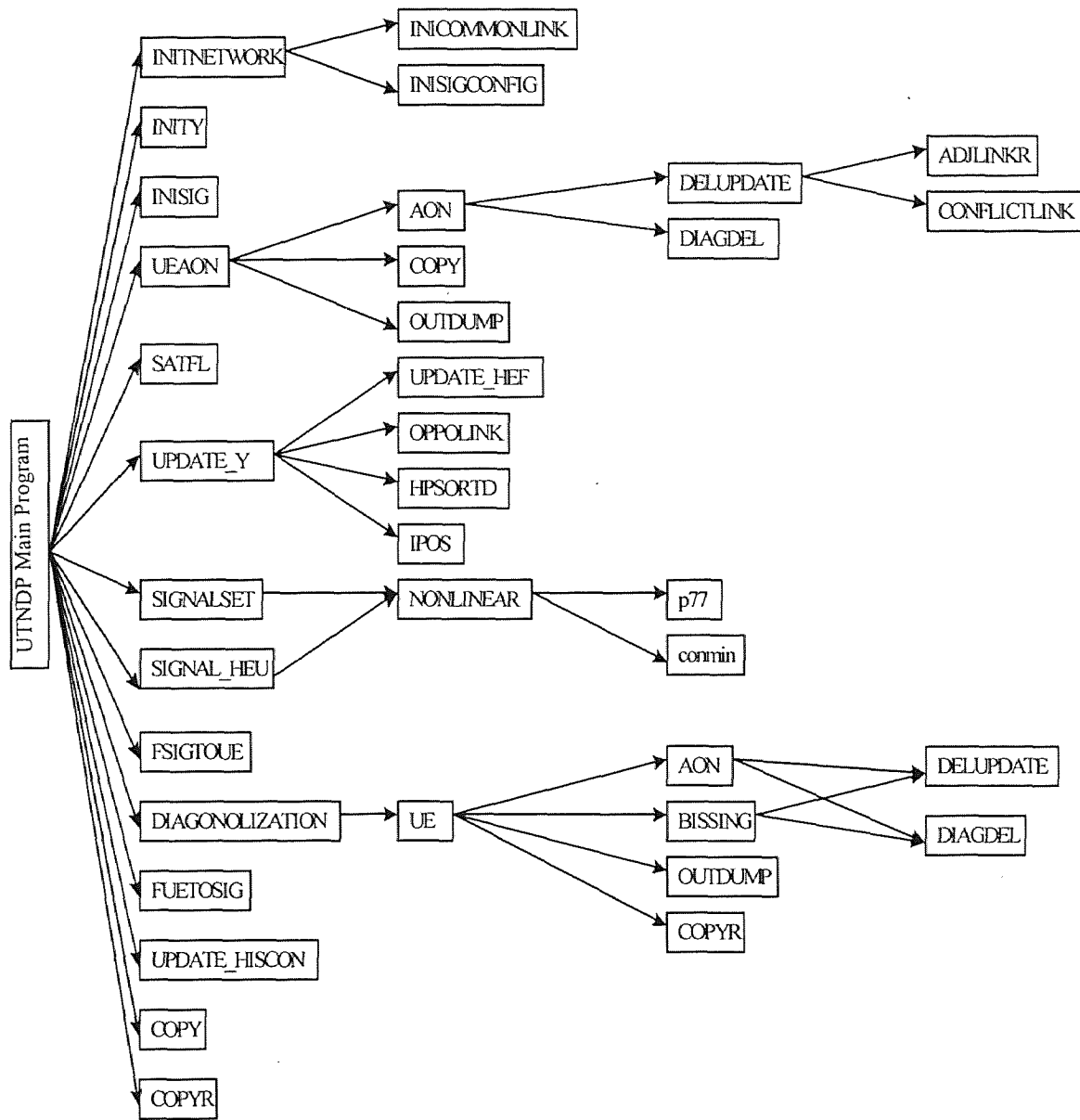
traffic assignment problems. Two important routines that work together with UE are ‘DELUPDATE’ and ‘DIAGDEL’. The first routine is used to update realistic link performance functions, while the second one is used to calculate the impact of conflicting opposite through movement on the delay of the subject left turning movement. Other major UTNDP subroutines include link-locating routines (‘OPPOLINK’, ‘ADJLINKR’ and ‘CONFLICTLINK’), and data format conversion routines (‘FUETOSIG’ and ‘FSIGTOUE’), which are used to connect major UTNDP components by converting the data format to a compatible form so that all programs can work together. Subroutine ‘conmin’ calls a set of programs developed by Dow (53); these programs are not included in Figure 4.1.

#### **4.2 The UTNDP Main Program**

The main UTNDP program follows the steps presented in section 3.2.1. These steps are: initialization, update upper level decision variable  $y$ , update saturation flow rates, solve signal setting, solve the lower level asymmetric UE traffic assignment, update historical contribution values, and heuristic search termination test. The UTNDP main program is presented in Figure 4.4.

There are two types of solution states in the UTNDP SA-TABU heuristic, the current state and the trial state. The current state is the accepted state with the accepted link flows, signal settings, and network configuration parameters. Trial states are generated based on the current state by perturbing network configuration variable  $y$ . Any changes in  $y$  lead to changes in the signal settings and link flows. The acceptance criteria in the heuristic search procedure of the UTNDP model are used to decide if a trial

state should either be accepted or rejected. An accepted trial state becomes the new current solution state, and new trial states will be generated based on it.



**Figure 4.1** UTNDP Program Subroutines

### 4.3 Initialization

This step reads the data by calling subroutines 'INITNETWORK', 'INITY' and 'INISIG' to solve the lower level UE traffic assignment, the upper level network configuration and the signal setting models. These data include the network configuration data, initial signal timing data, and O-D demand data, which are described below.

NARC: number of links,

NCENT: number of centroids,

NNOD: number of nodes,

NOD: number of O-D pairs,

TOO( ): link end node,

L( ): link length (mi),

V( ): speed limit (mph),

ASONODTURN( ): the associate node of a link. Each signalized intersection is represented by 8 nodes to describe intersection turning movements. The node with the smallest number is chosen as the associate node to represent the intersection.

STATUS( ): link status. Links are divided into 4 types, regular link, intersection left turn link, intersection through link, and intersection right turn link, which are represented by integer values 2, 3, 4 and 5, respectively. STATUS( ) is used to store these integers.

DIRECTION( ): DIRECTION ( ) provides the information designating the direction the link comes from. Links come from north, east, south, and west of an intersection and are represented by numbers 1, 2, 3, and 4, respectively.

TOD( ): end node of an O-D pair,

AMT( ): O-D demand,

ODLK( ): forward star array for the O-D matrix,

FS( ): forward star array for the links,

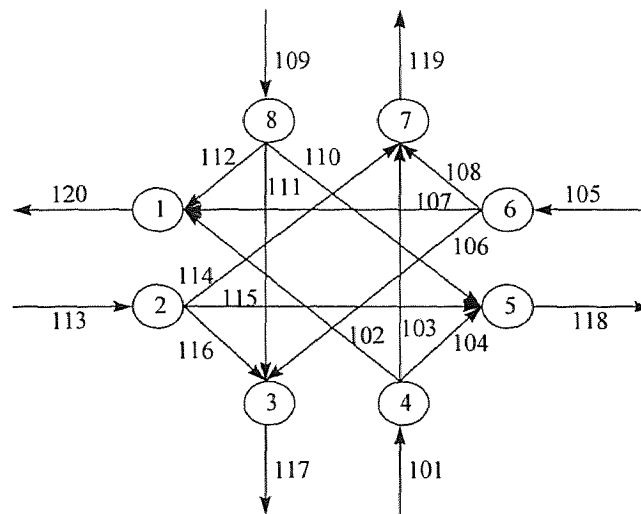
RNOD( ): node number,

NODETYPE( ): type of node. There are 2 types of nodes, signalized nodes and unsignalized nodes, represented by integer values 1 and 0, respectively.

GLST( ): the starting node of a signalized link,

GLEND( ): the ending node of a signalized link. A signalized link refers to a link that is associated with a set of signal setting variables. For each 4-leg intersection, the 4 regular links coming out from the intersection are considered as signalized links that are associated with the signal settings of the 4 approaches.

Using the intersection in Figure 4.2 as an example, the 4 signalized links are 117, 118, 119, and 120.



**Figure 4.2** An Expanded Signalized Intersection

The ASONODTURN, STATUS, and DIRECTION arrays represent the configuration of the network. Figure 4.2 presents a typical expanded signalized intersection.

Nodes 1 to 8 represent an expanded signalized intersection. Links 101 to 120 represent all the links associated with the intersection. The ASONODTURN, STATUS, and DIRECTION values of the links are described in Table 4.1.

**Table 4.1** Link Configuration Values of a Sample Intersection

| Link Number (I) | ASONODTURN(I) | STATUS(I) | DIRECTION(I) |
|-----------------|---------------|-----------|--------------|
| 101             | 1             | 2         | 3            |
| 102             | 1             | 3         | 3            |
| 103             | 1             | 4         | 3            |
| 104             | 1             | 5         | 3            |
| 105             | 1             | 2         | 2            |
| 106             | 1             | 3         | 2            |
| 107             | 1             | 4         | 2            |
| 108             | 1             | 5         | 2            |
| 109             | 1             | 2         | 1            |
| 110             | 1             | 3         | 1            |
| 111             | 1             | 4         | 1            |
| 112             | 1             | 5         | 1            |
| 113             | 1             | 2         | 4            |
| 114             | 1             | 3         | 4            |
| 115             | 1             | 4         | 4            |
| 116             | 1             | 5         | 4            |
| 117             | 1             | 2         | 3            |
| 118             | 1             | 2         | 4            |
| 119             | 1             | 2         | 2            |
| 120             | 1             | 2         | 1            |

Saturation flow rates and link flows are also initialized in this step, using subroutines 'SATFL' and 'UEAON', respectively. Subroutine 'SATFL' will be presented in section 4.5. The heuristic search related parameters, the initial temperature, initial Markov chain length, temperature dropping rate, Markov chain length increasing rate, TABU list length, and the weights of the 3 components of the HEF, are also initialized in this step.

#### 4.4 Update Upper Level Decision Variable $y$

At each UTNDP iteration, the upper level decision variable  $y$  (lane designation and intersection movement control variables) are updated based on the HEF values and the TABU status of each link. The HEF has three components, the link v/c ratio, the historical contribution, and the random factors. The link v/c ratio reflects the current traffic performance on the subject link. Since the objective of the UTNDP is to minimize network-wide link travel time, the larger the heuristic value is, the better the chance that the subject link is chosen to be updated. This is because links with high v/c ratios often experience much larger delays than links with low v/c ratios. For the two types of updateable links, the calculation of v/c ratio for regular links is straightforward, while the calculation of the v/c ratio for left turn intersection links requires lane group status information. If the subject left turn, the corresponding through and right turn intersection links are in one lane group, the v/c ratio of this whole lane group is calculated and assigned to the left turn link. If the subject left turn intersection link is in a separate lane group, its v/c ratio is calculated separately. The difference between the network UE total travel time of the trial state and the current state is calculated, stored and accumulated as the historical contribution of the trial state  $y$  value of the updated link. If the network-wide UE total travel time of the trial state is less than that of the current state, then a negative historical contribution of the trial  $y$  value is recorded. The smaller the historical contribution value is, the less chance the subject link has to be chosen as the candidate link to be updated. If the trial state solution is better than the current best solution, the trial  $y$  value is rewarded by multiplying the historical contribution by a credit factor larger than 1.

Subroutine 'UPDATE\_Y' is used to update the upper level decision variable  $y$ . The input of subroutine 'UPDATE\_Y' is  $YIN()$ , the output is  $YOUT()$ , representing the updated  $YIN()$ . The link with the highest HEF value among all the links not in the TABU lists is selected to be updated, because high HEF values represent inappropriate traffic performance on the link. Subroutine 'UPDATE\_Y' starts with calling a subroutine 'UPDATE\_HEF' to update HEF values. Then subroutine 'HPSORTD' is called to sort the HEF values in descending order, where the sorted HEF values are stored in array  $HEFORD()$ . Another subroutine 'IPOS' is called to match elements in  $HEFORD()$  with their original index in  $HEF()$ , and the matched indexes are stored in  $IPOS1()$ . The current TABU status  $TABUSTATUS(I)$  stores the most recent iteration number under which link  $I$  is updated. The difference between the current iteration number  $ITE$  and  $TABUSTATUS(I)$  represents the number of iterations in which link  $I$  hasn't been changed. If this difference is greater than a preset TABU length value, then link  $I$  is updateable. Otherwise, the TABU status prevents link  $I$  from being updated. If the selected link is a regular link, an additional lane is added to the link to alleviate the condition of the link, and one lane has to be reduced from the opposite link. Update the temporary TABU status  $TEMPSTATUS()$  for both the subject link and its opposite link to  $ITE$ . If the selected link is a left turn link, and it is in a separate lane group, then update  $YIN(IPOS1(I))$  from 1 to 0, and set the  $TEMPSTATUS()$  of the selected left turn link to  $ITE$ . If the selected link is a left turn link and it is in the same lane group with the through and right turn links, then update  $YIN(IPOS1(I))$  from its current state (0 or 1) to a new state (1 or 0), set  $TEMPSTATUS()$  of the selected left turn link to  $ITE$ . When the left turn link is in the same lane group with the through and the right turn links, its HEF



value is composed of the historical contribution factor, the random factor, and the v/c ratio of the whole lane group rather than those of the left turn link itself. The flow chart of subroutine 'UPDATE\_Y' is presented in Figure 4.6. Every time y is updated, a trial state is created. Under the trial state, signal setting and traffic assignment subroutines are performed, and the results are checked to decide if the trial state is accepted as the current state. If the trial state is accepted, TEMPSTATUS( ) is copied to TABUSTATUS( ).

#### 4.5 Update Saturation Flow Rates

Based on link flows, network configuration, and lane group designations, the saturation flow rates that will be used to construct both the objective function and the capacity constraints in the signal setting model need to be updated prior to the signal setting and the UE traffic assignment steps.

Subroutine 'SATFL' starts with checking the status of the subject link. If link I is a regular link, the saturation flow rate is calculated as:

$$STF(I) = Y(I) \times 1900 \times a_w \times a_{HV} \times a_g \times a_p \times a_{bb} \times a_a.$$

The number of lanes of this regular link is represented by  $Y(I)$ , while all the other parameters are the same as described in equation (3.28). If link I is a through or a right turn link, STF(I) is temporarily set to 9999, which is updated after the corresponding left turn intersection link is checked. If link I is a left turn intersection link, it could be designated as a separate left turn lane group, or the left turn, through, and the right turn links are designated as one lane group. The lane group designation not only depends on

the flows of these links themselves, but also on the traffic flow of the opposite through link, which is called the conflicting flow. Subroutines 'CONFLICTLINK' and 'ADJLINKR' are called to find the conflicting link and the approaching regular-in link. If the regular-in link only has one lane, all movements are designated as one lane group, otherwise, check opposite through link flow  $f_o$  to decide the appropriate lane group designation. If  $f_o$  is greater than 1400, link I is treated as a separate left turn lane group,  $STF(I) = 1900 \times \gamma$ ,  $\gamma$  is a constant which varies with  $f_o$ . The saturation flow rate of the other lane group (composed of through and right turn movements) is estimated as:

$$STF(I) = (Y(k) - 1) \times 1900 \times a_w \times a_{HV} \times a_g \times a_p \times a_{bb} \times a_a \times a_{RT}$$

$k$  is the approaching regular-in link. In the UTNDP model, left, through and right turn movements are ordered as I, I+1, and I+2. Since through and right turns are always in one lane group,  $STF(I+2)$  need not be estimated in this subroutine. If  $f_o$  is less than 1400, FLLE(I) (the left turn volume equivalent) and AVGFL (the average volume of the through and the right turn lane group) are calculated. If FLLE(I) is less than or equal to AVGFL, then the left turn link I is in a separate lane group, and  $STF(I)$  and  $STF(I+1)$  are estimated the same way as described before. If FLLE(I) is greater than AFGFL, all movements are designated as one lane group, and the saturation flow rate is calculated as:

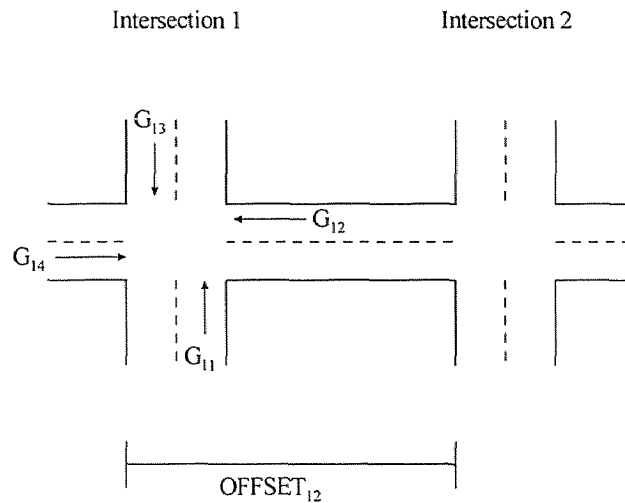
$$STF(I + 1) = Y(k) \times 1900 \times a_w \times a_{HV} \times a_g \times a_p \times a_{bb} \times a_a \times a_{RT} \times a_{LT}.$$

To estimate  $a_{LT}$ , calculate  $g_f$  (average amount of green time before the arrival of the first left turn vehicle),  $g_u$  (the average amount of green time after the arrival of the first left turn), and  $P_L$  (the proportion of left turn vehicle in the left lane), using the methods proposed in section 3.2.3. The flow chart of subroutine 'SATFL' is presented in Figure 4.6.

#### 4.6 Solve Signal Setting

In each UTNDP iteration, signal settings are set by calling subroutine 'SIGNALSET'. All other offsets other than the ones directly optimized by the signal setting model can be calculated by calling subroutine 'OTHEROFFSET'.

Subroutine 'SIGNALSET' is used to obtain optimal green splits and offsets. The green splits and offsets for a typical 4-leg intersection are presented in Figure 4.3:



**Figure 4.3** Signal Setting Variables

$G_{11}$ ,  $G_{12}$ ,  $G_{13}$  and  $G_{14}$  represent the effective green times allocated to the 4 approaches of intersection 1. Variable  $\phi_{12}$  represents the offset between intersection 1 and 2. The following equations have to be satisfied:

$$G_{11} = G_{13}$$

$$G_{12} = G_{14}$$

$$G_{11} + G_{12} = \text{cycle length (Or. } G_{13} + G_{14} = \text{cycle length)}$$

Given any of the 4 green splits, the others can be derived from the above equations. So, for each intersection, only one green split variable, namely  $G_{11}$ , is used in the signal setting model as a decision variable. All the other green splits are represented as a function of  $G_{11}$ , and their contributions to the objective function are also represented by  $G_{11}$ . By doing so, both the number of decision variables and the number of constraints can be reduced significantly in the signal setting model. To obtain reasonably good signal setting results, the UTNDP is solved 12 times using fixed cycle length ranging from 60 to 120 seconds with 5 second increments, and then the result with the smallest network wide total travel time is selected as the solution of the signal setting model.

Given link flows and the network configuration variable  $y$ , subroutine 'SIGNALSET' must be solved before proceeding to the lower level UE traffic assignment step. However, there is the possibility that subroutine 'SIGNALSET' doesn't have a solution. If this happens, the program goes back to subroutine 'UPDATE\_Y' to choose another  $y$  to be updated. If after a number of trials, the 'SIGNALSET'

subroutine is still not solvable, then reinitialize the green splits, offsets, and the cycle length, and proceed to the asymmetric traffic assignment subroutine

‘DIAGONALIZATION’. The search is then directed to a new search area, starting with initial signal settings and current link flows. The flowchart of this process is presented in Figure 4.7.

The data format of the link flows and saturation flows, which are obtained from the ‘DIAGONALIZATION’ subroutine and used as input to subroutine ‘SIGNALSET’, is not compatible with the requirements of subroutine ‘SIGNALSET’. Similarly, the signal setting results, which are obtained from ‘SIGNALSET’ and used as input to subroutine ‘DIAGONALIZATION’ are not compatible with the requirements of ‘DIAGONALIZATION’ either. Before calling ‘SIGNALSET’, subroutine ‘FUETOSIG’ is called to convert link flows and saturation flows to a format compatible with ‘SIGNALSET’. After ‘SIGNALSET’, subroutine ‘FSIGTOUE’ is called to convert signal setting results to a format compatible with ‘DIAGONALIZATION’.

#### **4.7 Solve the Lower Level Asymmetric UE Traffic Assignment**

The existence of the asymmetric impact of the opposite through vehicles on the left turn vehicles requires a diagonalization procedure to solve the lower level UE traffic assignment. The diagonalization is achieved by approximating the asymmetric problem with a series of symmetric problems. Symmetric problems are solved using the Frank-Wolfe algorithm.

One of the major differences between this study and previous traffic assignment studies is that a more realistic link performance function is used rather than the BPR

curve. The performance function is described in section 3.1.2. The independent variables of the performance function not only include link flows, but also signal timings and saturation flow rates. Subroutine 'DELUPDATE' is used to update the link performance function in this study.

The diagonalization of an asymmetric traffic assignment problem requires a link performance function that includes both the subject link flow and the conflicting flows as independent variables. So far, no such functions have been proposed. In this study, a left turn adjustment factor is used to account for the impact of the conflicting opposite through movement on the left turn movement delays. Subroutine 'DIAGDEL' is designed for this purpose. Subroutines 'DELUPDATE' and 'DIAGDEL' are discussed in the next paragraph.

In subroutine 'DELUPDATE', if the subject link  $I$  is a regular link, the delay on the link  $DL(I)$  is estimated using equations (3.21) and (3.22). If link  $I$  is a left turn link and it is in a separate lane group, calculate uniform delay  $DU(I)$  and random delay  $DA(I)$  using equations (3.14) and (3.15), respectively. The link flows, saturation flows and signal timings on link  $I$  are obtained and used as inputs to subroutine 'DELUPDATE'. The corresponding through and right turn delay  $DL(I+1)$  and  $DL(I+2)$  are calculated in the same way. If link  $I$  is a left turn link and left, through and right turn movements are in one lane group, the delay on the approaching regular-in link  $DL(J)$  is calculated. Then the delay on the subject left turn link  $DL(I)$  and the delays on the through and right turn links  $DL(I+1)$  and  $DL(I+2)$  are derived from  $DL(J)$  using equation (3.24). In subroutine 'DELUPDATE', 'ADJLINKR' and 'CONFLICTLINK' are called to find the

approaching regular-in link J and the conflicting opposite through link K. Subroutine 'DELUPDATE' is presented in Figure 4.8.

In subroutine 'DIAGDEL', if link I is a left turn link, calculate the average amount of green time before the arrival of the first left turn vehicle  $GF(I)$ , and the average amount of green time required for the opposing standing queue to clear  $GQ(I)$ , using equations (3.34) and (3.35), respectively. Call subroutine 'CONFLICTLINK' to find the conflicting opposite through link K. If  $FLDG(K)$ , the flow on link K from the last iteration, is greater than 1400, then no left turn vehicle could be cleared at the intersection, and the through car equivalent factor  $EL$  is assigned a very large value. Otherwise, calculate  $EL$  as proposed in section 3.2.3. If  $GQ(I)$  is greater than  $GF(I)$ , then  $GU$ , the average amount of green time after the arrival of the first left turn vehicle that is not blocked by the clearance of the opposing standing queue, equals to green  $G(I)$  minus  $GQ(I)$ . Otherwise,  $GU$  equals to  $G(I)$  minus  $GF(I)$ . The proportion of left turn vehicles in the left lane  $PL$  is calculated using equation (3.33). The left turn adjustment factor  $FLL$  is calculated using equations (3.30)-(3.32). Finally, the delay estimated using the subject link flow is converted to the delay that reflects the impact of the opposing through movement by multiplying  $FLL$ . The flow chart of subroutine "DIAGDEL" is presented in Figure 4.9.

#### 4.8 Update Historical Contribution

The inclusion of the historical contribution factor in the HEF provides an additional element in the search that rewards upper level decision variables  $y$  that performed well in the previous iterations. By introducing the historical contribution factor, the search

becomes more informed and more focused on high quality feasible regions. Although this may increase the risk of not finding the global optimal solution, it can increase the efficiency of the search strategy significantly. Considering the computational complexity of an UTNDP, it is necessary to find near optimal solutions within a reasonable number of iterations. The inclusion of the historical contribution as one component of the HEF may greatly reduce the number of iterations of finding a near optimal solution.

In each UTNDP iteration, historical contribution factors are only updated for the links whose decision variable values are changed. Therefore, only left turn links and regular links are associated with historical contribution values. There are two states of  $y$  variables for left turn links,  $y$  either equals to 0 or equals to 1 (representing permission and prohibition of the left turn movement, respectively). For regular link  $y$  variables, the possible values are 1, 2 and 3, representing the number of lanes, respectively. For each state of a  $y$  variable, there is an associated historical contribution value. The historical contribution values of left turn links are stored in a 2-dimentional array  $HISCONI(i,j)$ , while the historical contribution values of regular links are stored in  $HISCONR(i,j)$ . Here,  $i$  represents the state of the  $y$  variable, and  $j$  represents the link number. The historical contribution of a  $y$  state of a link is an accumulation of the performance index of the state. The performance index used in this study is the difference between the network-wide total travel times of the current state and the trial state. Each time the link is updated, the difference is calculated and accumulated to the historical contribution value. To better explain the mechanism of the process of calculating historical contribution, two examples are given in the subsequent paragraphs. The first example is designed for a left turn link, and the second one is designed for a regular link.



Example 1:

Given,

$i$ : number of a left turn link updated in the trial state,

$HISCONI(i,1)$ : current historical contribution of state  $y(i)=0$ ,

$HISCONI(i,2)$ : current historical contribution of state  $y(i)=1$ ,

Current State:  $y(i)=0$

Trial State:  $y(i)=1$

Current State Network Total Travel Time:  $TRTIME\_C$

Trial State Network Total Travel Time:  $TRTIME\_T$

Current Contribution:  $RIMP = TRTIME\_C - TRTIME\_T$

The historical contribution after the solution of the trial state is:

$HISCONI(i,1) = HISCONI(i,1) + RIMP$

$HISCONI(i,2) = HISCONI(i,2) - RIMP$

The contribution of  $y(i)$  changing from state 0 to state 1 is represented by  $RIMP$ .

If  $RIMP$  is negative, the solution of current state is better than that of trial state.

Therefore,  $HISCONI(i,1)$  is credited by reducing its value by the amount of  $RIMP$ , and

$HISCONR(i,2)$  is penalized by increasing its value by the amount of  $-RIMP$ . If  $RIMP$  is

positive, the solution of the current state is worse than that of trial state. Therefore,

$HISCONI(i,1)$  is penalized by increasing its value by the amount of  $RIMP$ , and

$HISCONI(i,2)$  is credited by reducing its value by the amount of  $-RIMP$ . The  $y$  states of

links with small historical contribution values are considered as good candidates of

entering the final solution set, and they are less likely to be chosen as the links to be

updated.

Example 2:

Given,

i: number of a regular link updated in the trial state,

HISCONR(i,1): current historical contribution of state  $y(i)=1$ ,

HISCONR(i,2): current historical contribution of state  $y(i)=2$ ,

HISCONR(i,3): current historical contribution of state  $y(i)=3$ ,

Current State:  $y(i)=2$

Trial State:  $y(i)=3$

Current State Network Total Travel Time: TRTIME\_C

Trial State Network Total Travel Time: TRTIME\_T

Current Contribution:  $RIMP = TRTIME\_C - TRTIME\_T$

The historical contribution after the solution of the trial state is:

$HISCONR(i,1) = HISCONR(i,1)$

$HISCONR(i,2) = HISCONR(i,2) + RIMP$

$HISCONR(i,3) = HISCONR(i,3) - RIMP$

In example 2,  $y(i)$  is updated to  $y(i)=3$ , therefore,  $HISCONR(i,1)$ , which represents the state of  $y(i)=0$ , remains unchanged.

Subroutine 'UPDATE\_HISCON' is designed for the purpose of updating historical contributions. If link I is a left turn link and the current state is  $Y(I)=0$ , credit/penalize  $HISCON(I,1)$  by adding RIMP to its current value, while at the same time penalize/credit  $HISCON(I,2)$  by subtracting RIMP from its current value. If link I is a regular link and the current state is  $Y(I)=1$ ,  $Y(I)$  can only be updated to  $Y(I)=2$ , therefore, credit/penalize  $HISCONR(I,1)$  by adding RIMP, penalize/credit  $HISCONR(I,2)$  by

subtracting RIMP from its current value. If link I is a regular link and the current state is  $Y(I)=3$ ,  $Y(I)$  can only be updated to  $Y(I)=2$ , therefore, credit/penalize  $HISCONR(I,3)$  by adding RIMP, and penalize/credit  $HISCONR(I,2)$  by subtracting RIMP from its current value. If link I is a regular link, current state is  $Y(I)=2$  and trial state  $YOUT(I)=1$ , then credit/penalize  $HISCONR(I,2)$  by adding RIMP, penalize/credit  $HISCONR(I,1)$  by reducing RIMP from its current value. If link I is a regular link, the current state is  $Y(I)=2$ , and the trial state is  $YOUT(I)=3$ , then credit/penalize  $HISCONR(2,I)$  by adding RIMP, penalize/credit  $HISCONR(I,3)$  by reducing RIMP from its current value.

Subroutine 'UPDATE\_HISCON' is presented in Figure 4.10.

UTNDP Main Program Flow Chart

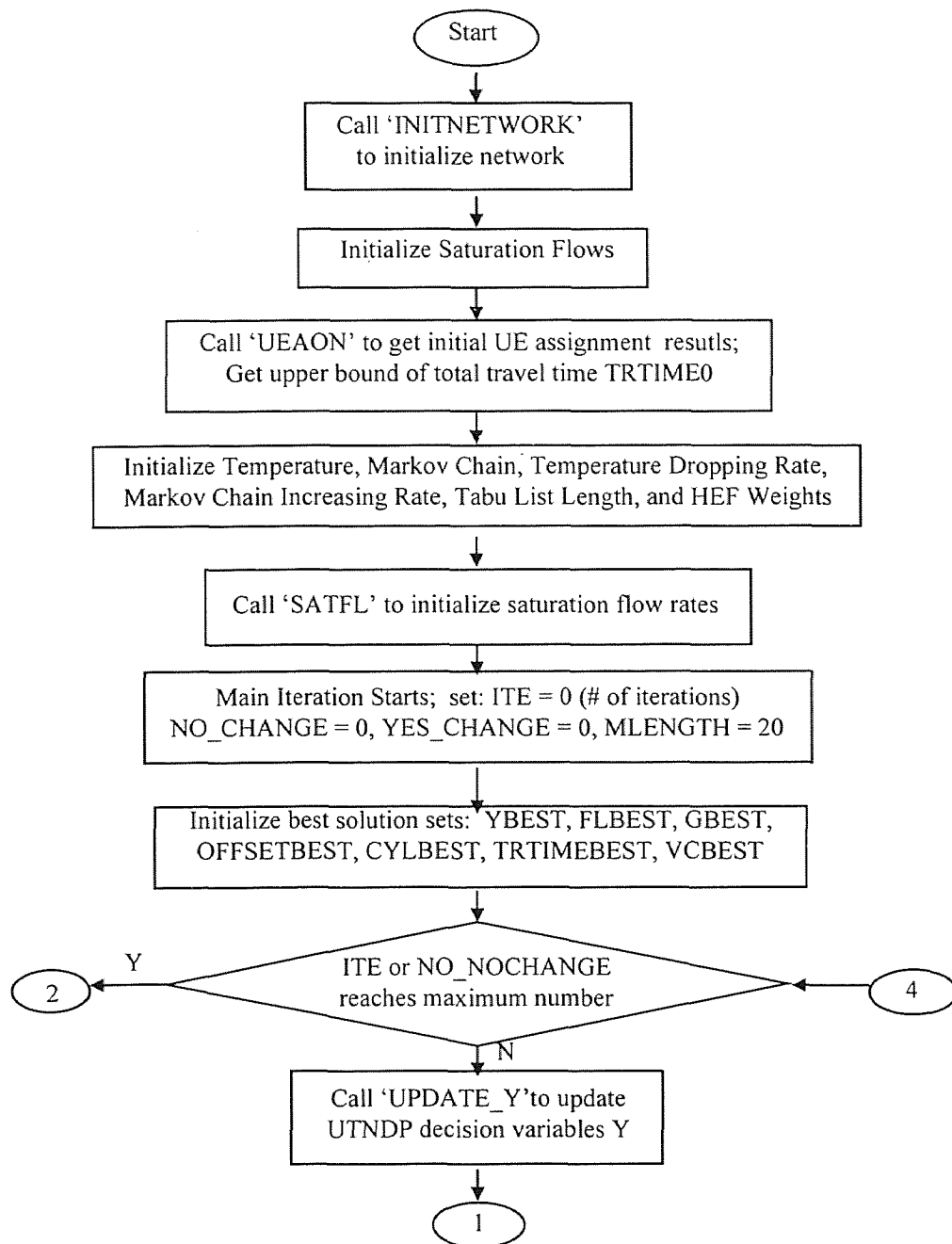
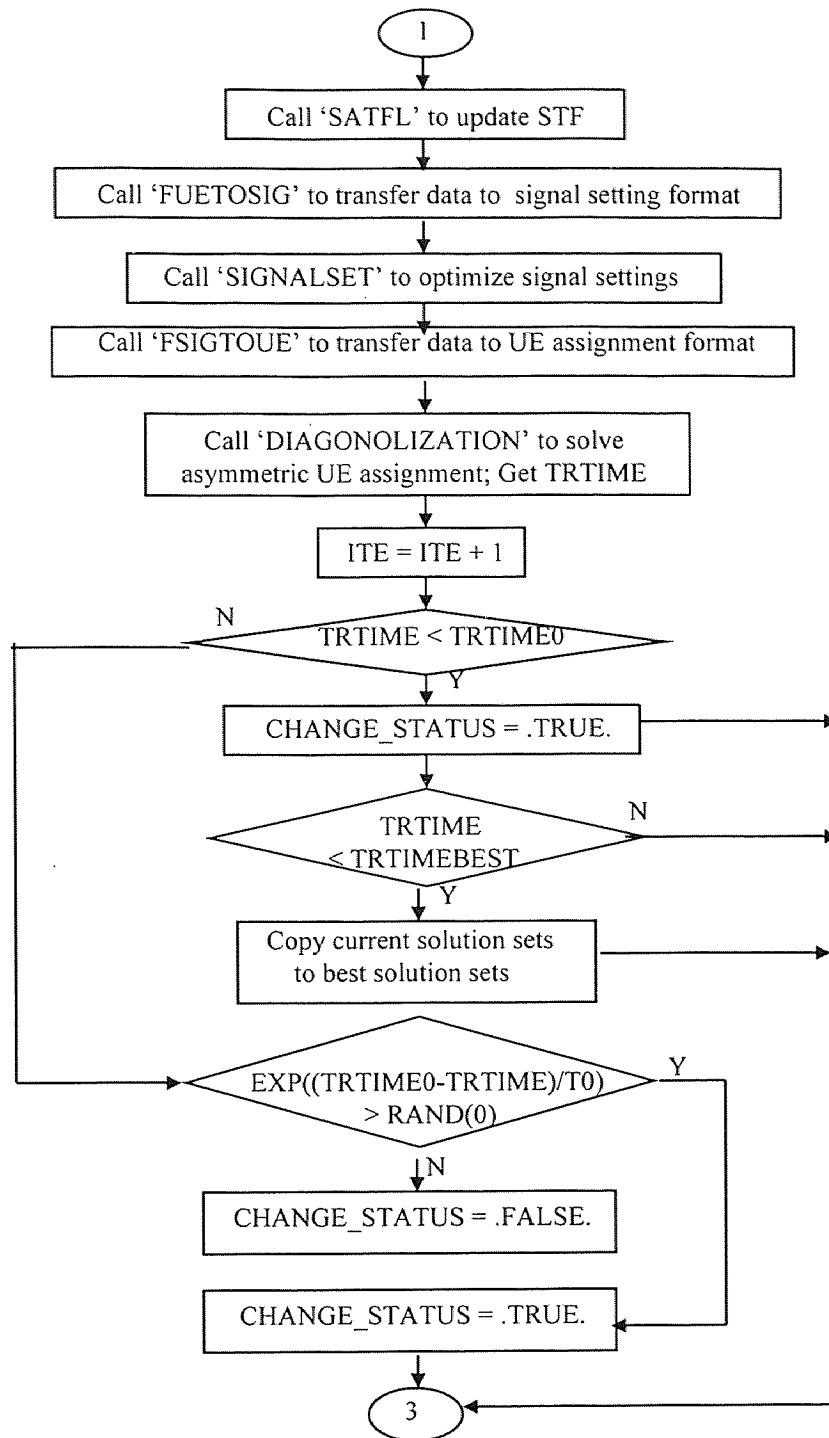
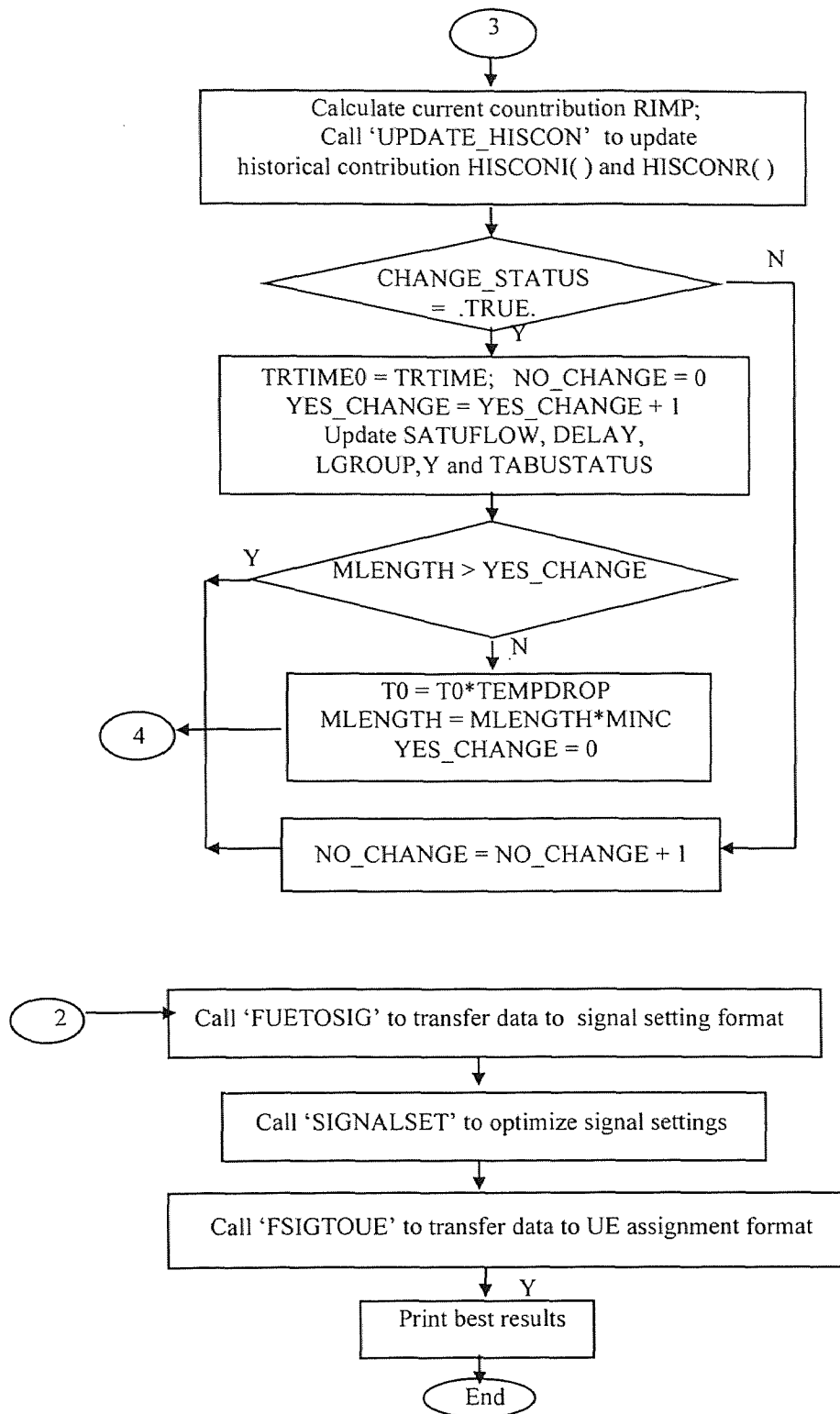


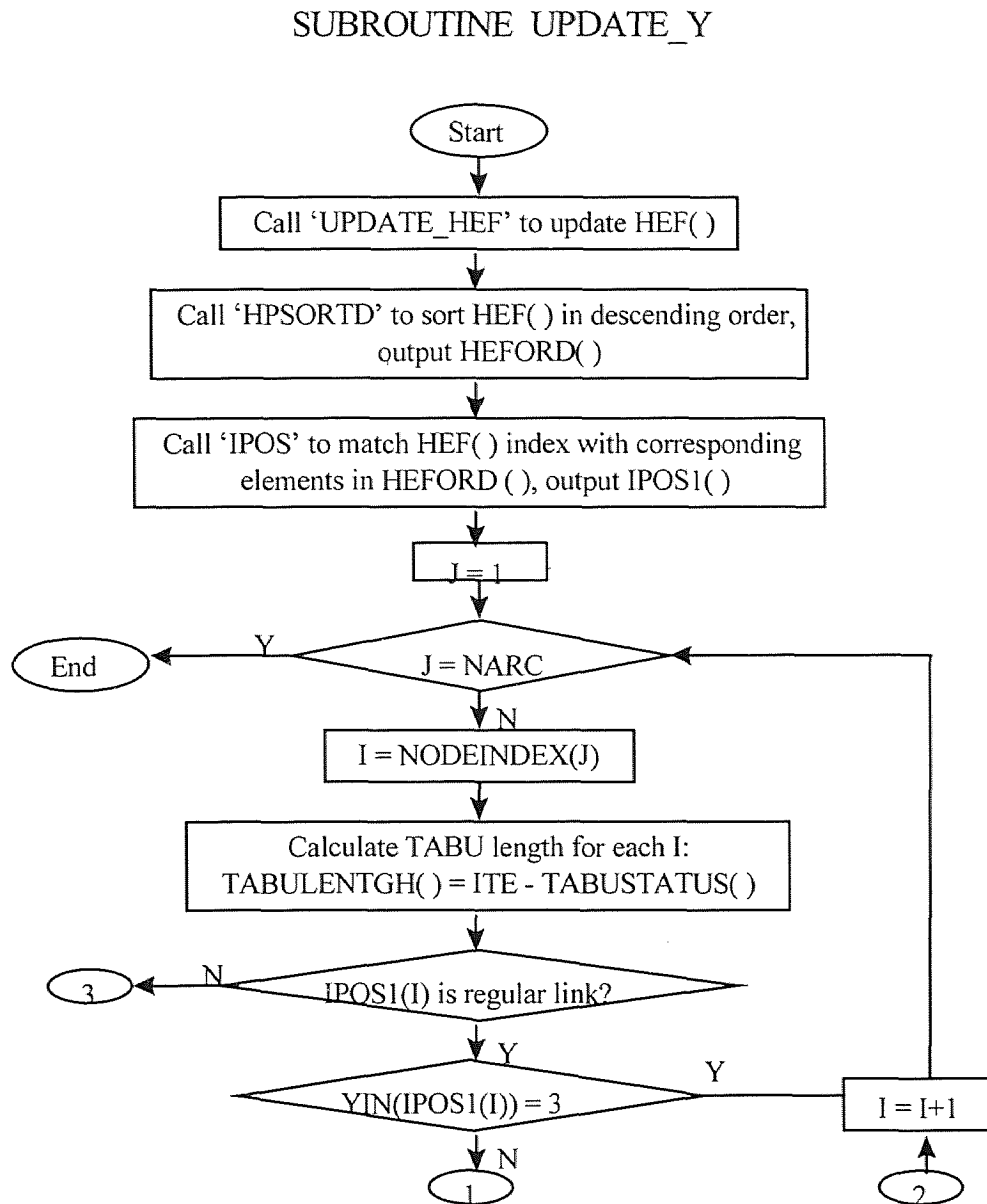
Figure 4.4 The UTNDP Main Program



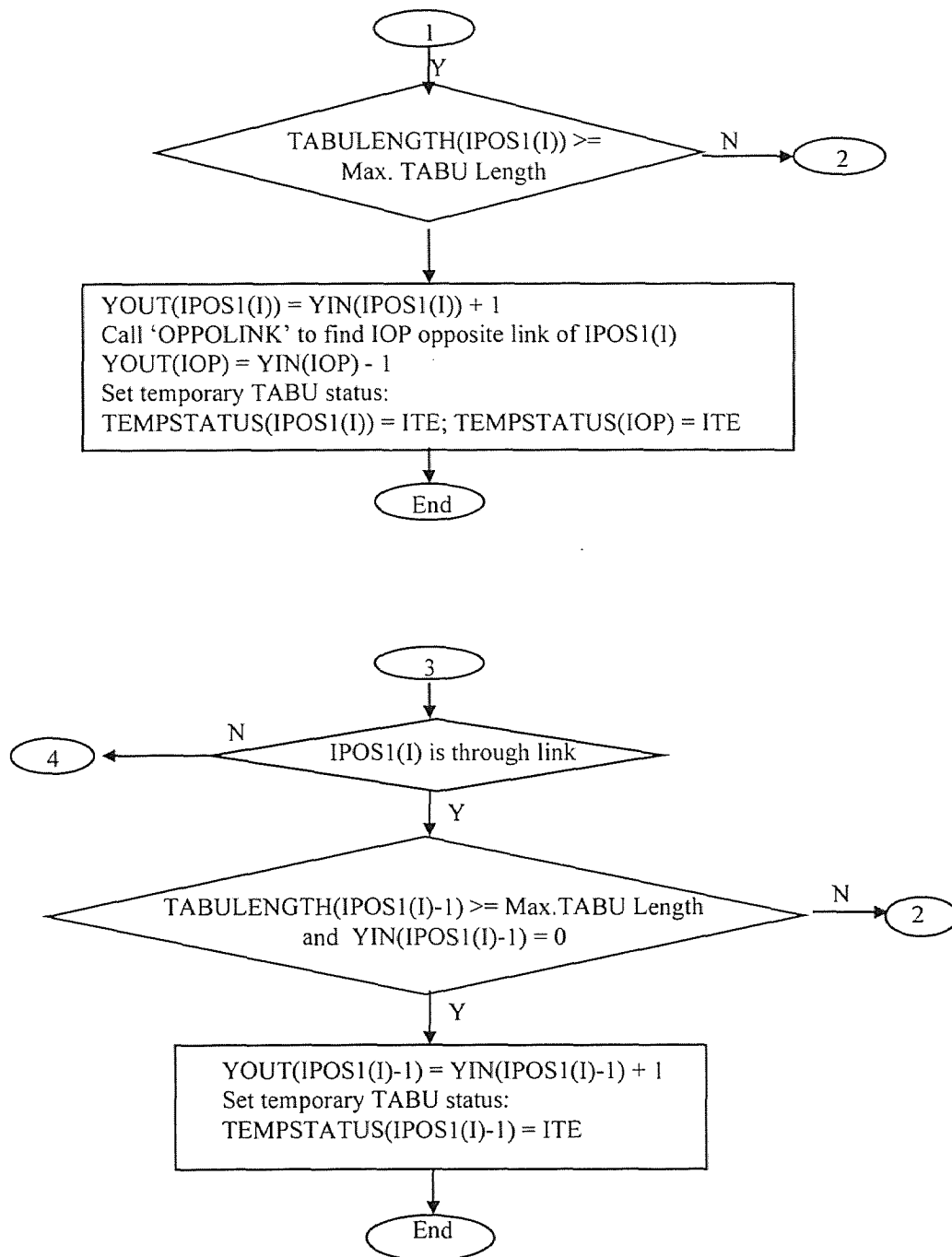
**Figure 4.4** The UTNDP Main Program (Continued)



**Figure 4.4** The UTNDP Main Program (Continued)

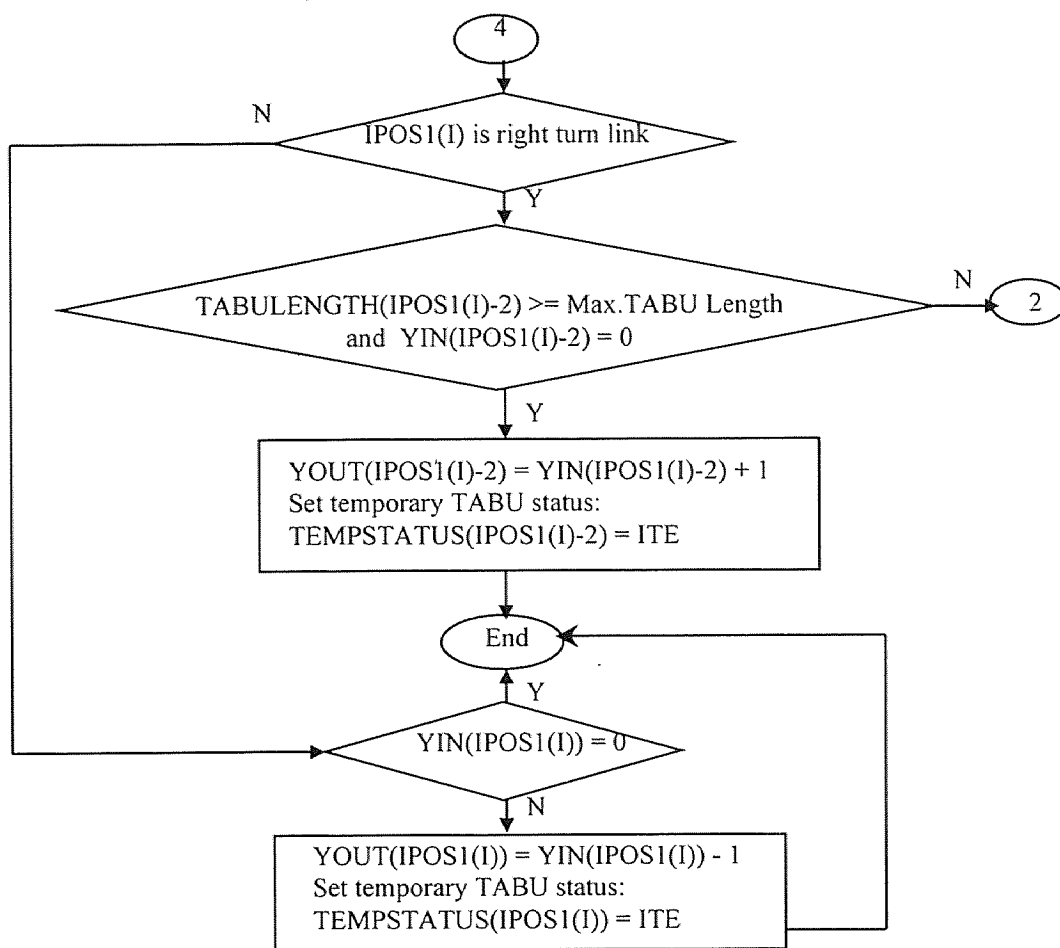


**Figure 4.5** Subroutine UPDATE-Y



**Figure 4.5** Subroutine UPDATE-Y (Continued)





**Figure 4.5** Subroutine UPDATE-Y (Continued)

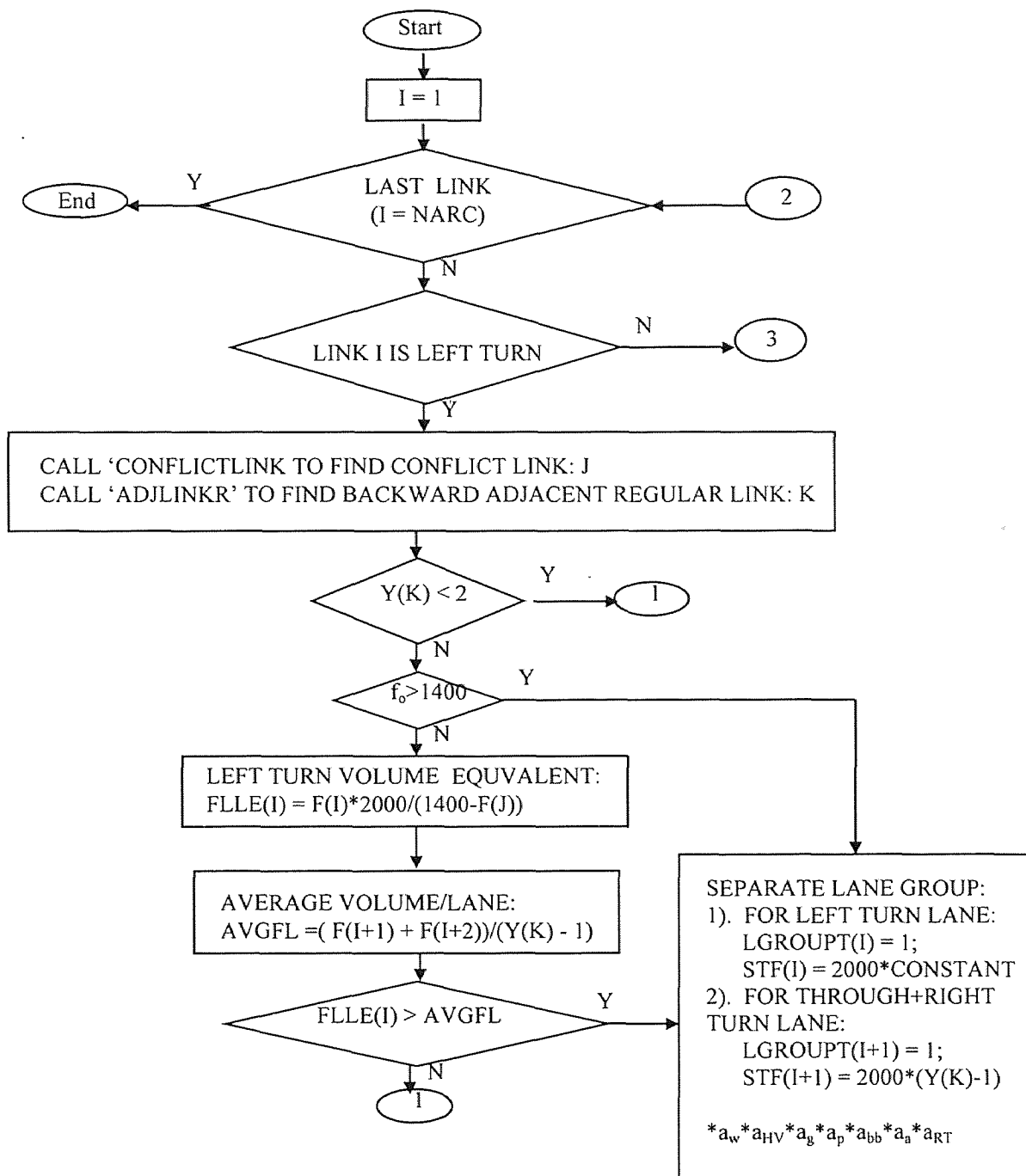
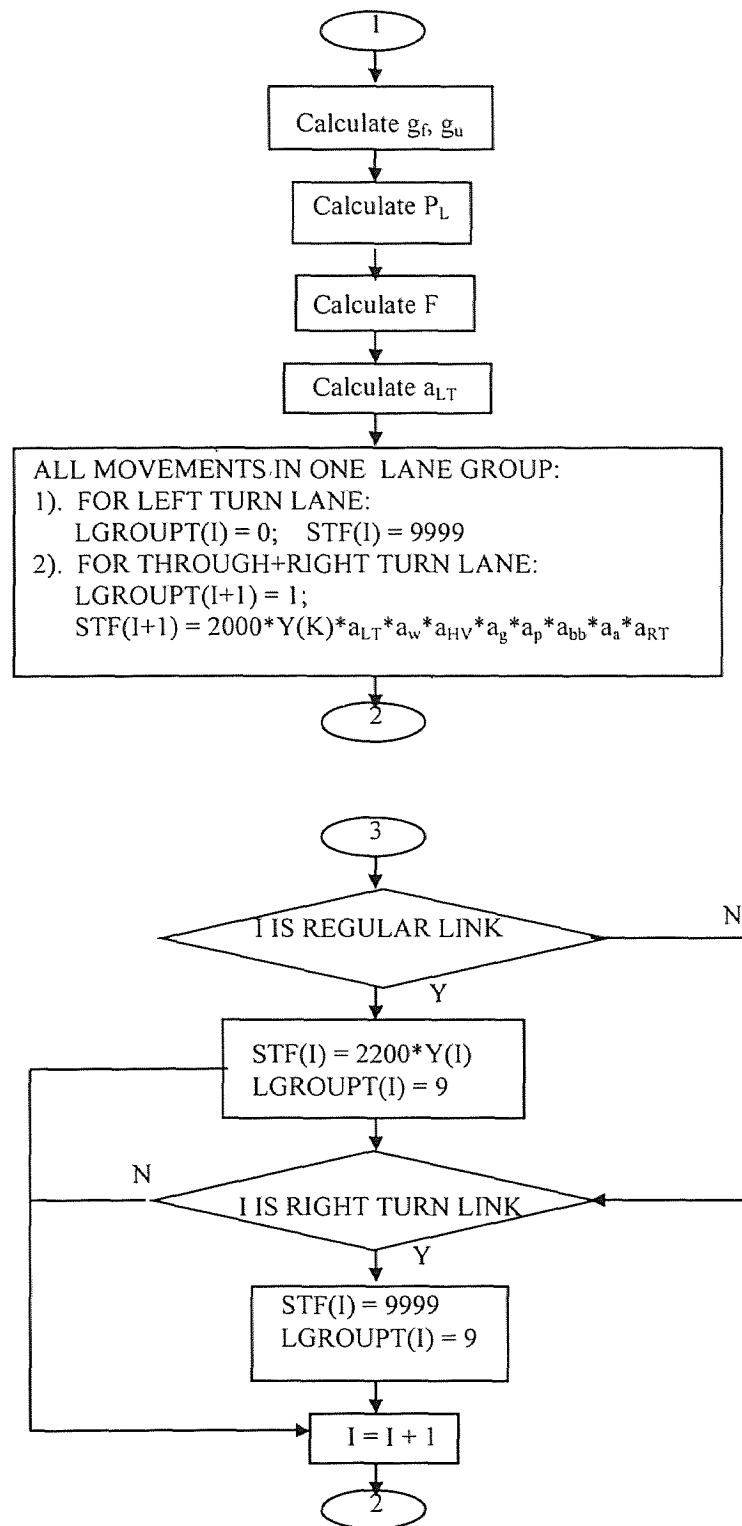
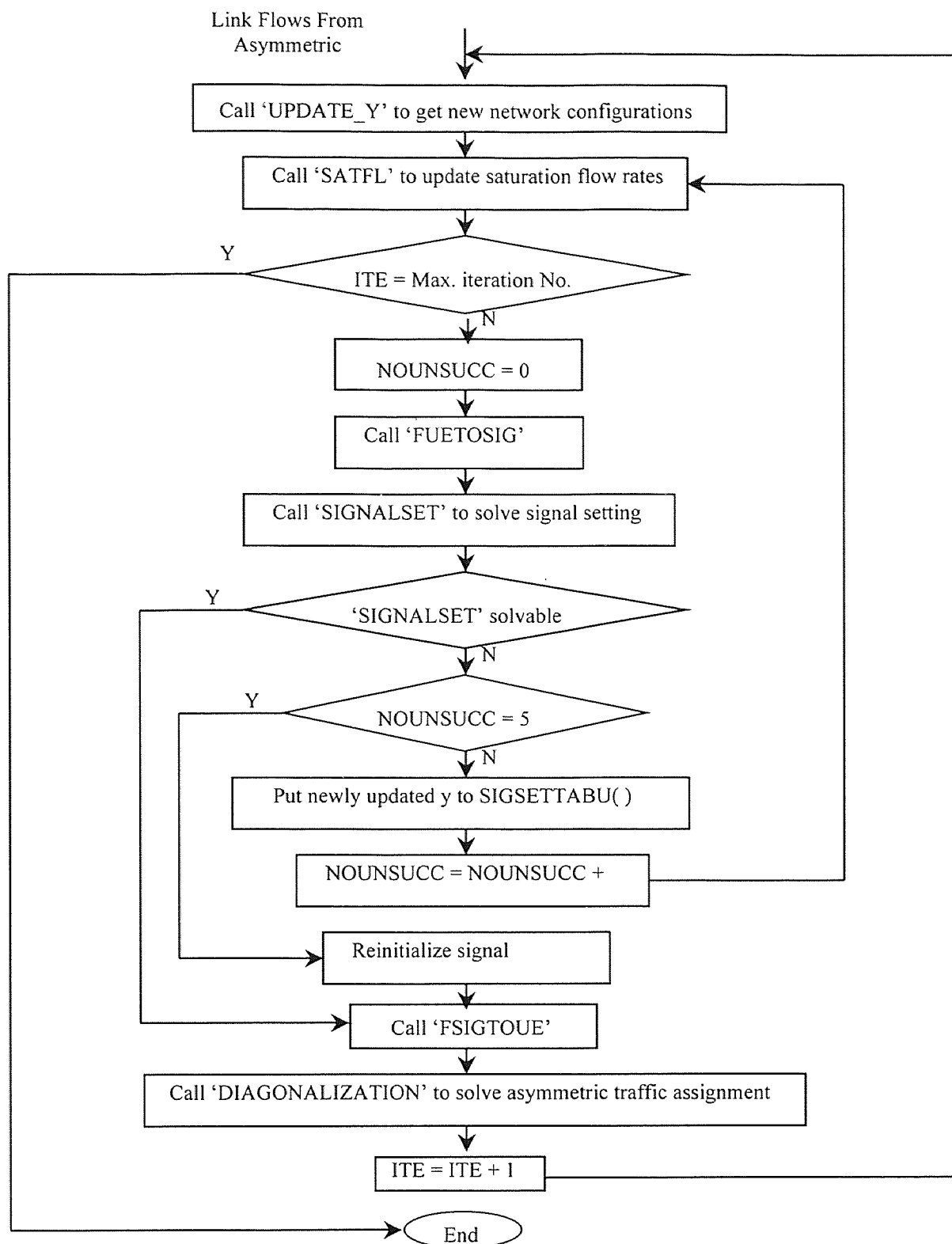


Figure 4.6 Subroutine SATFL



**Figure 4.6** Subroutine SATFL (Continued)



**Figure 4.7** Iterations of Signal Setting in UTNDP Main Program

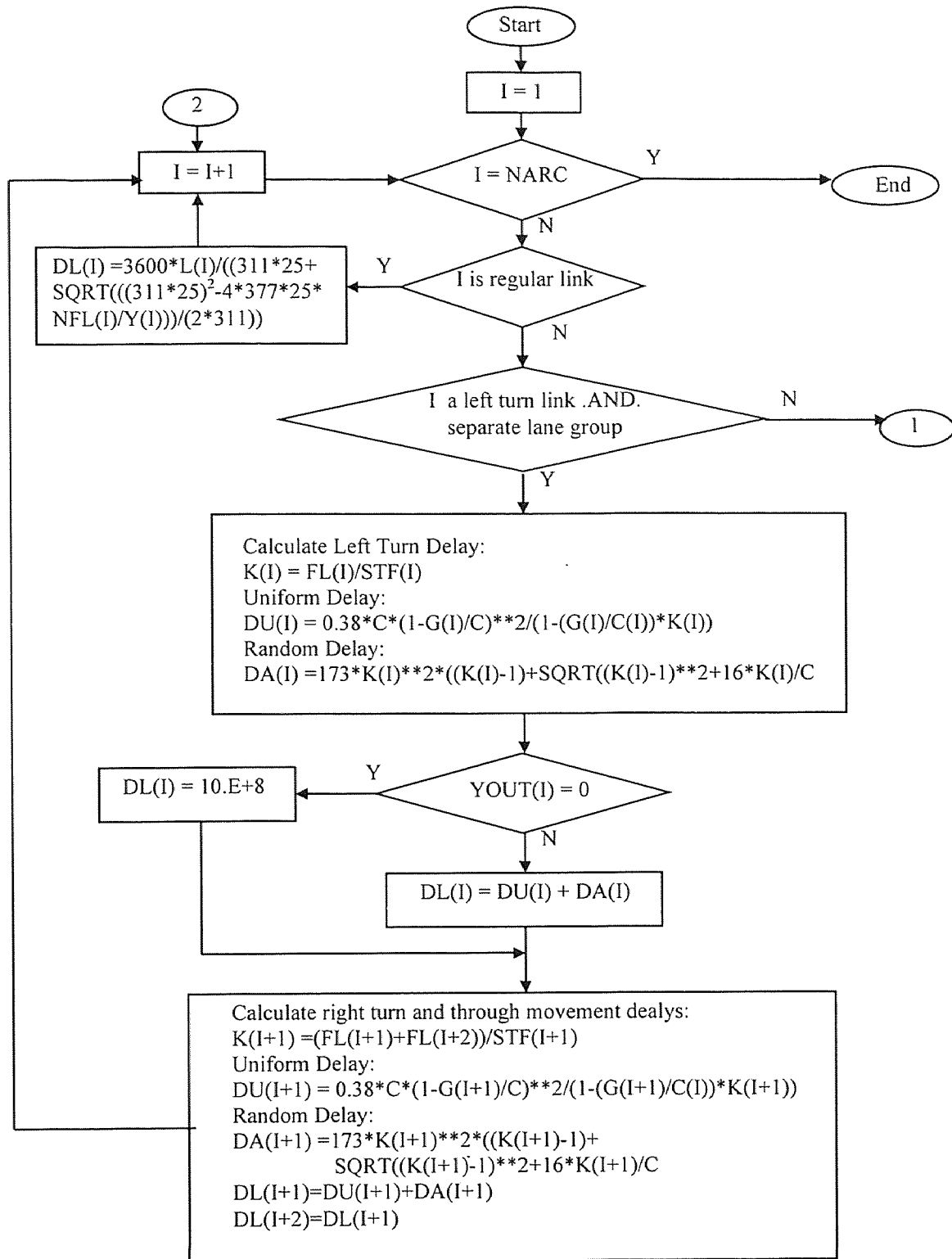


Figure 4.8 Subroutine DELUPDATE

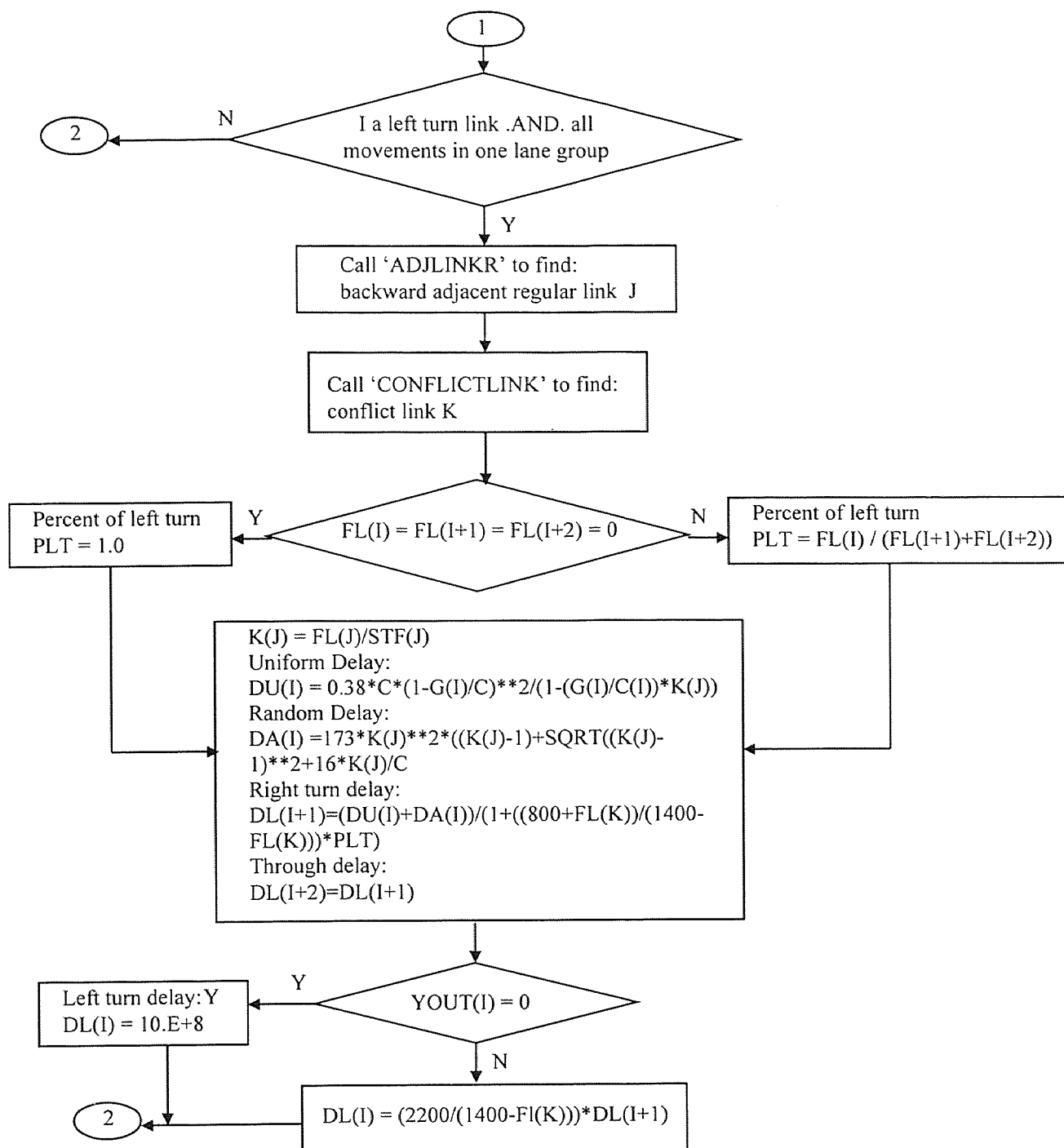


Figure 4.8 Subroutine DELUPDATE (Continued)

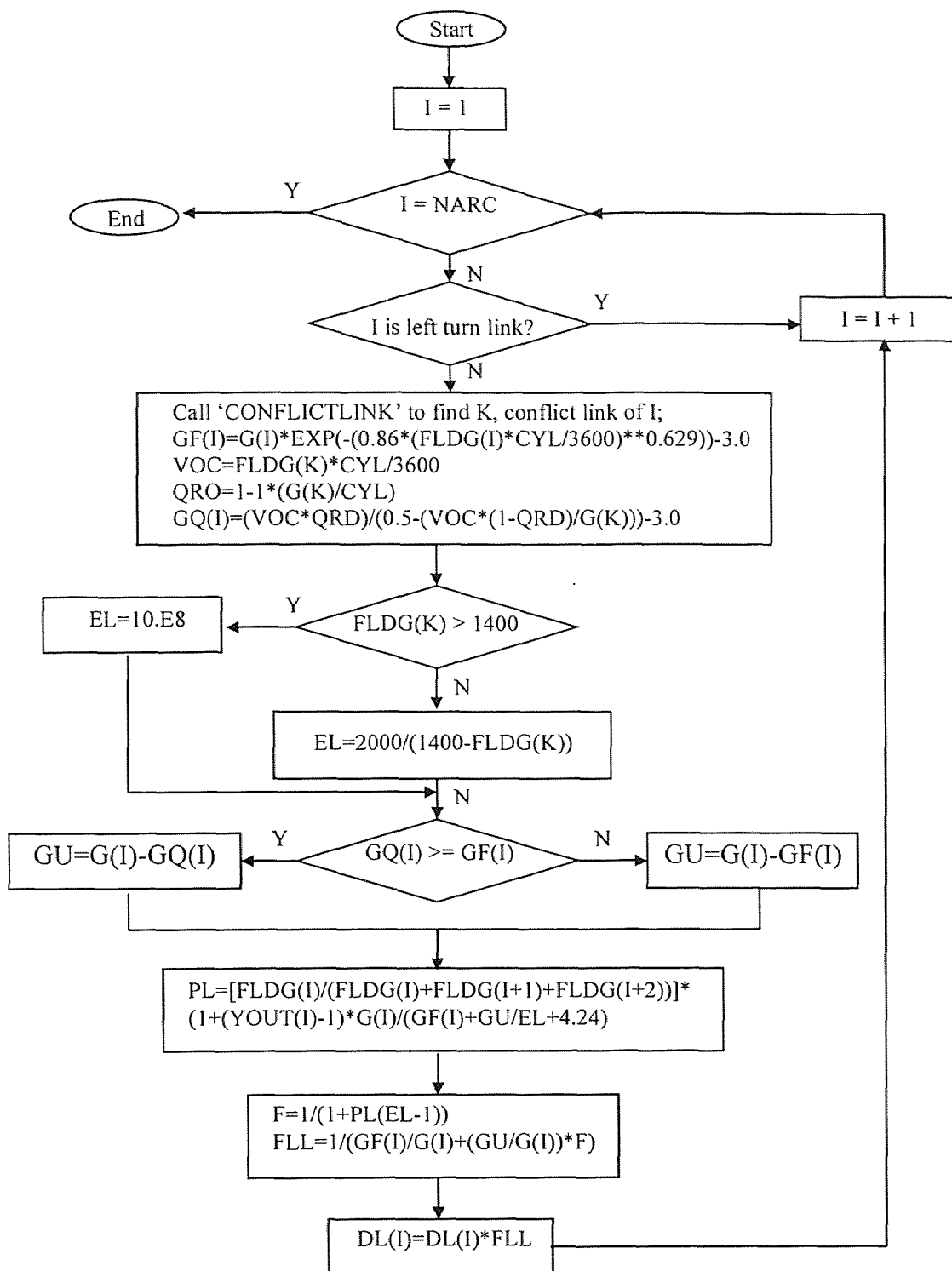
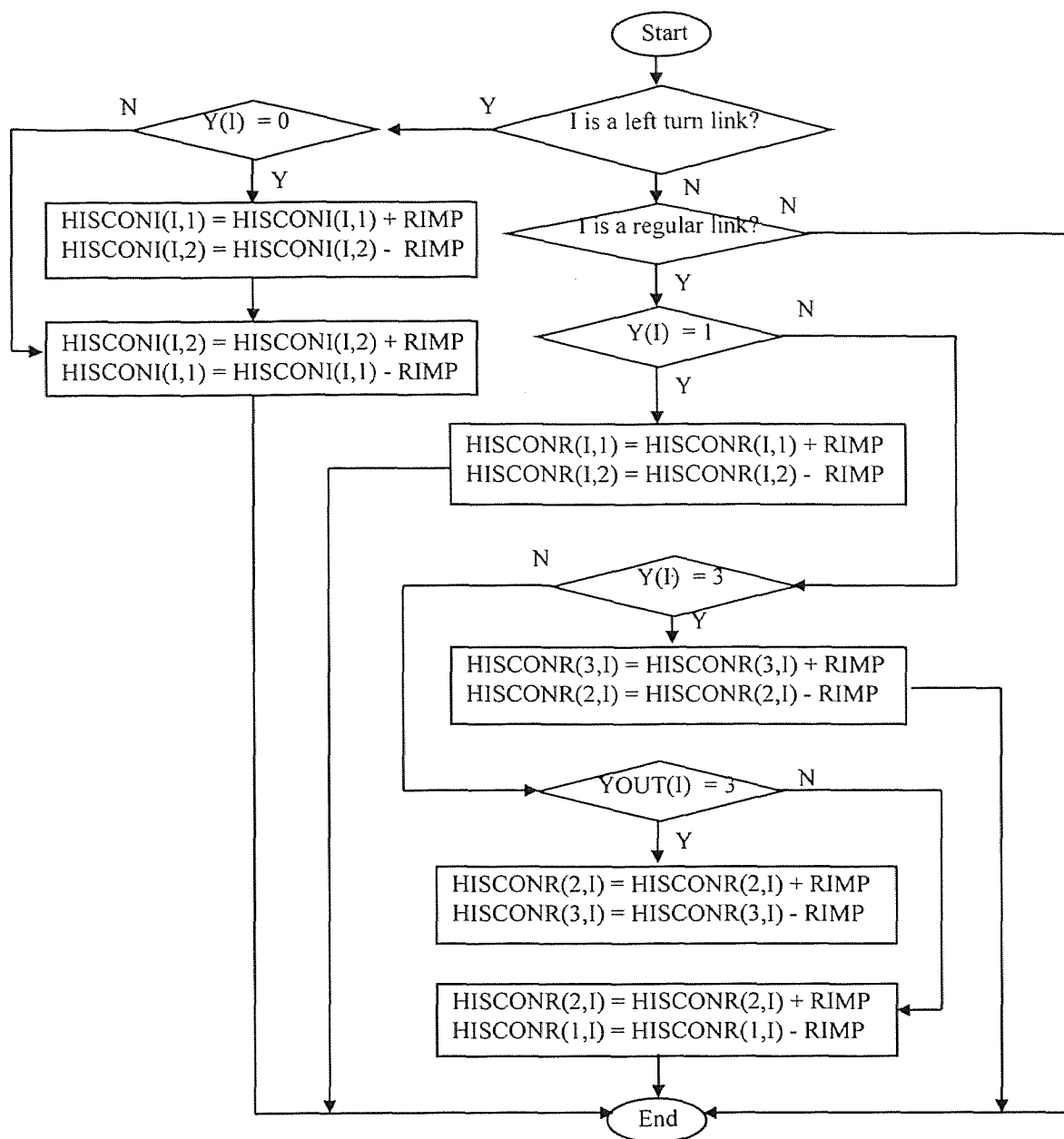


Figure 4.9 Subroutine DIAGDEL



**Figure 4.10** Subroutine UPDATE-HISCON



## **CHAPTER 5**

### **NUMERICAL EXPERIMENTS**

This chapter presents numerical experiments of the SA-TABU based methodology to solve the UTNDP outlined in Chapter 3. The primary objectives of these experiments are to examine the characteristics of the solutions generated by this procedure. The computational performance and the sensitivity on major algorithmic parameters of the SA-TABU heuristic are presented in Chapter 6.

The SA-TABU search strategy used in this study is a heuristic that combines the characteristics of simulated annealing and TABU search methods. Although the SA-TABU heuristic can not guarantee an optimal solution, it is an efficient method that can be used to locate reasonably good solutions within an acceptable amount of computational time. To test the efficiency of the SA-TABU search procedure, the numerical experiments need to cover as many networks with different configurations and characteristics as possible. In this study, 4 small to medium sized networks are used for experimental purposes, which are described in section 5.1, followed by the analysis of the results.

#### **5.1 Test Networks**

Among the 4 test networks, 3 of them are grid networks, Network 1 (3 by 3), Network 2 (3 by 4), Network 4 (3 by 5), and the other one, Network 3, is an arterial. Network 4 includes 15 signalized intersections and can be used to represent a real urban network. Therefore, Network 4 is used as the base-network of the traffic signal engineering analysis of the solutions generated by the SA-TABU heuristic. The competition of

network resources, namely signal resources, between adjacent streets makes it very difficult to achieve good traffic performance on all streets in a network. Priority is often given to a major street or arterial that has heavy traffic. To study the performance of the UTNDP model on an isolated street, an arterial with 6 signalized intersections is included. The two smaller grid networks, together with the arterial, are used to conduct the sensitivity analysis for the parameters of the SA-TABU search due to their relatively small sizes. Turning movement control is one of the major concerns of this study. In order to represent turning movements in a network, signalized intersections of test networks need to be expanded using abstract intersection links as demonstrated in Figure 4.2. The structural and traffic characteristics of the four test networks are presented in the subsequent sections.

### **5.1.1 Test Network Characteristics**

Network 1: A graphical representation of network 1 is presented in Figure 5.1. Network 1 is a 3 by 3 grid network with 5 signalized intersections. This network has 4 centroids, 13 nodes and 32 links in the original network, and 56 nodes and 96 links in the expanded network.

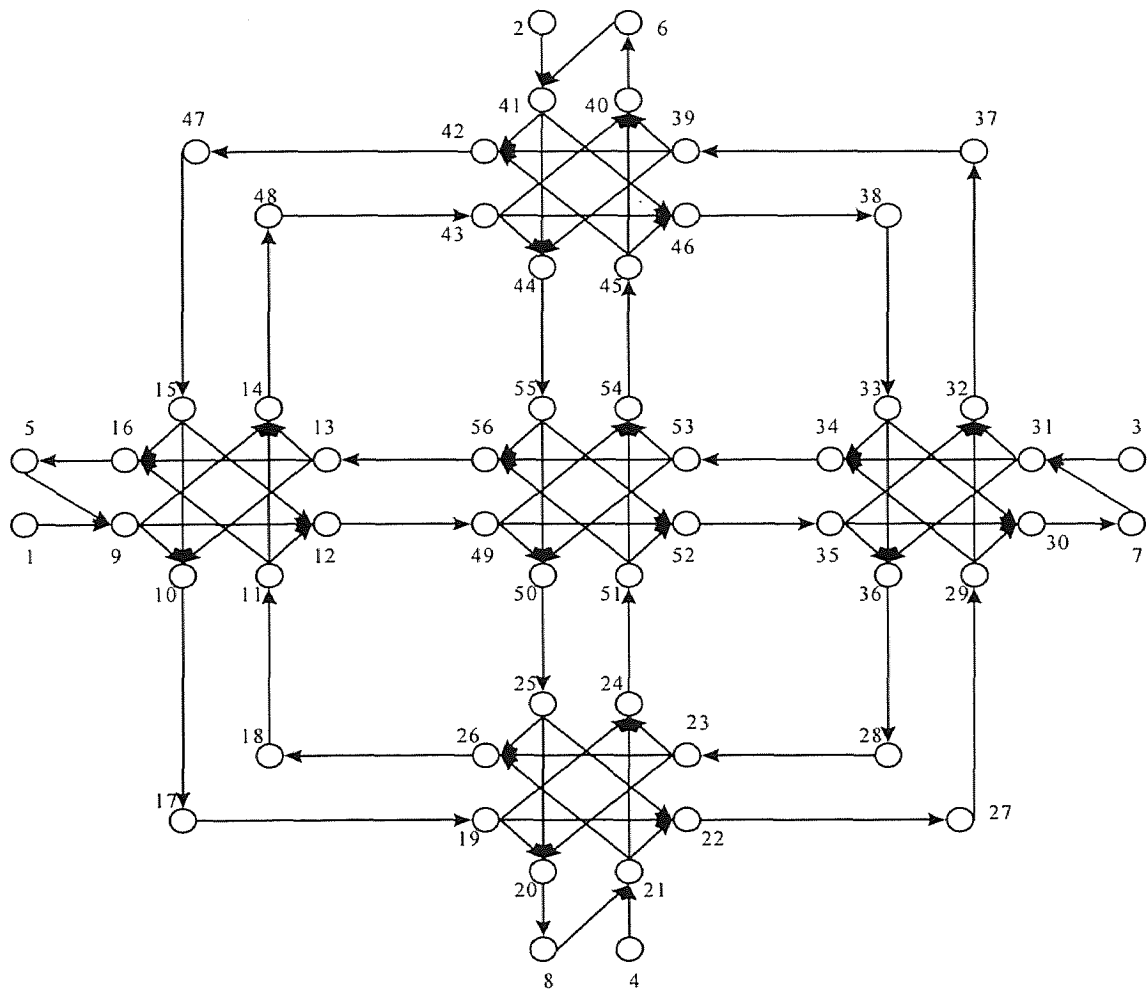
Network 2: A graphical representation of network 2 is presented in Figure 5.2. Network 2 is a 3 by 4 grid network with 8 signalized intersections. This network has 6 outside centroids and 1 internal centroid, 19 nodes and 62 links in the original network, and 94 nodes and 180 links in the expanded network.

Network 3: A graphical representation of network 3 is presented in Figure 5.3. Network 3 is an arterial with 6 signalized intersections. This network has 14 centroids,

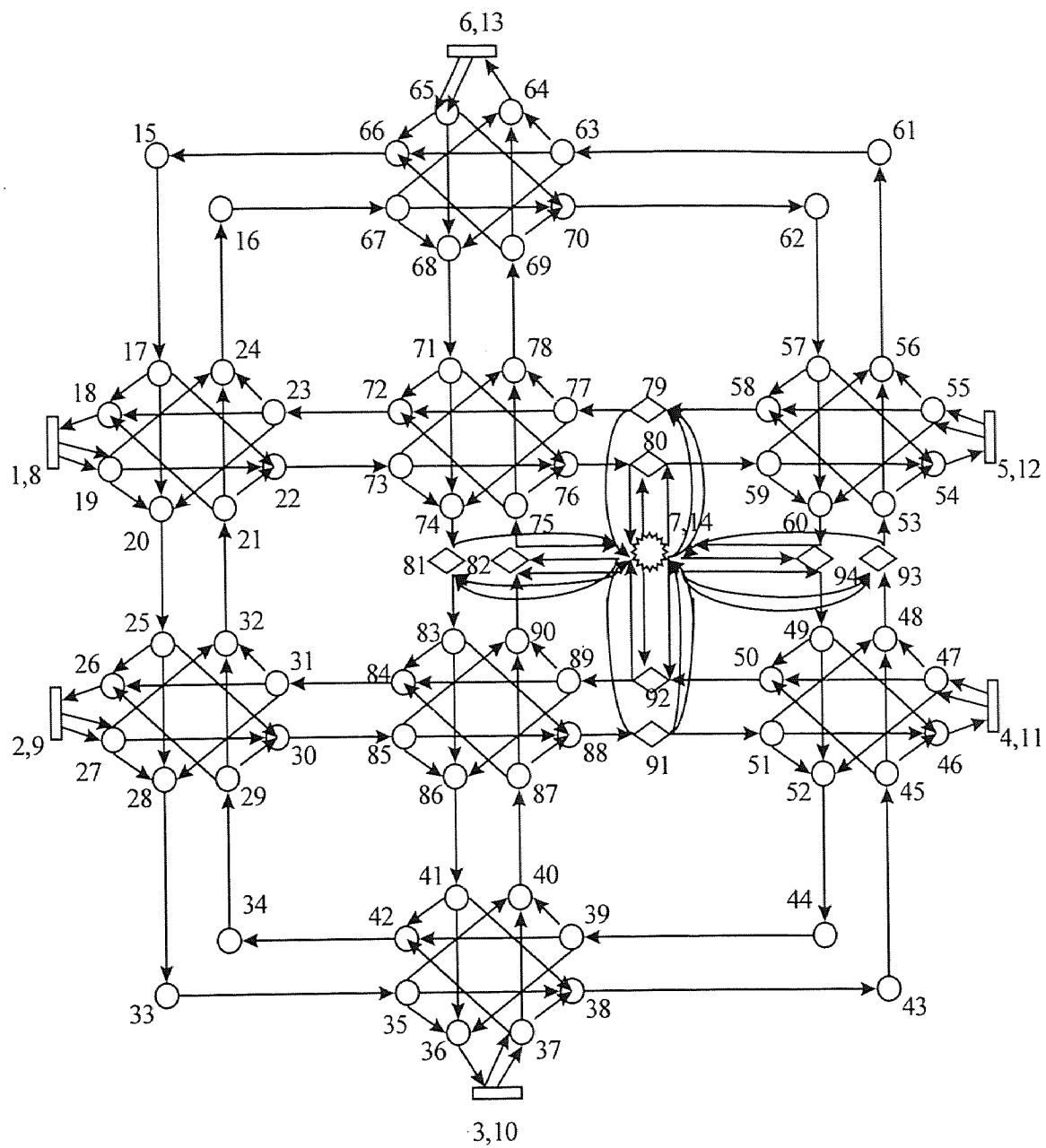
20 nodes and 38 links in the original network, and 76 nodes and 124 links in the expanded network.

Network 4: A graphical representation of network 4 is presented in Figure 5.4.

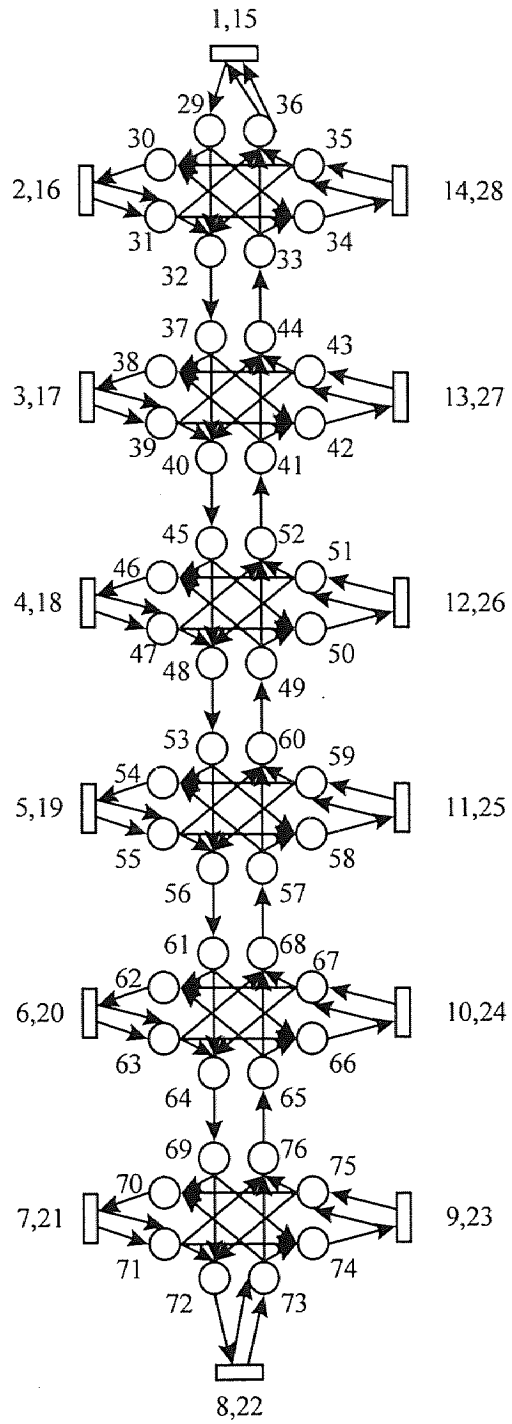
Network 4 is a 3 by 5 grid network with 15 signalized intersections. This network has 16 centroids, 31 nodes and 76 links in the original network, and 152 nodes and 272 links in the expanded network. The length of each link ranges from 0.1 to 0.4 miles.



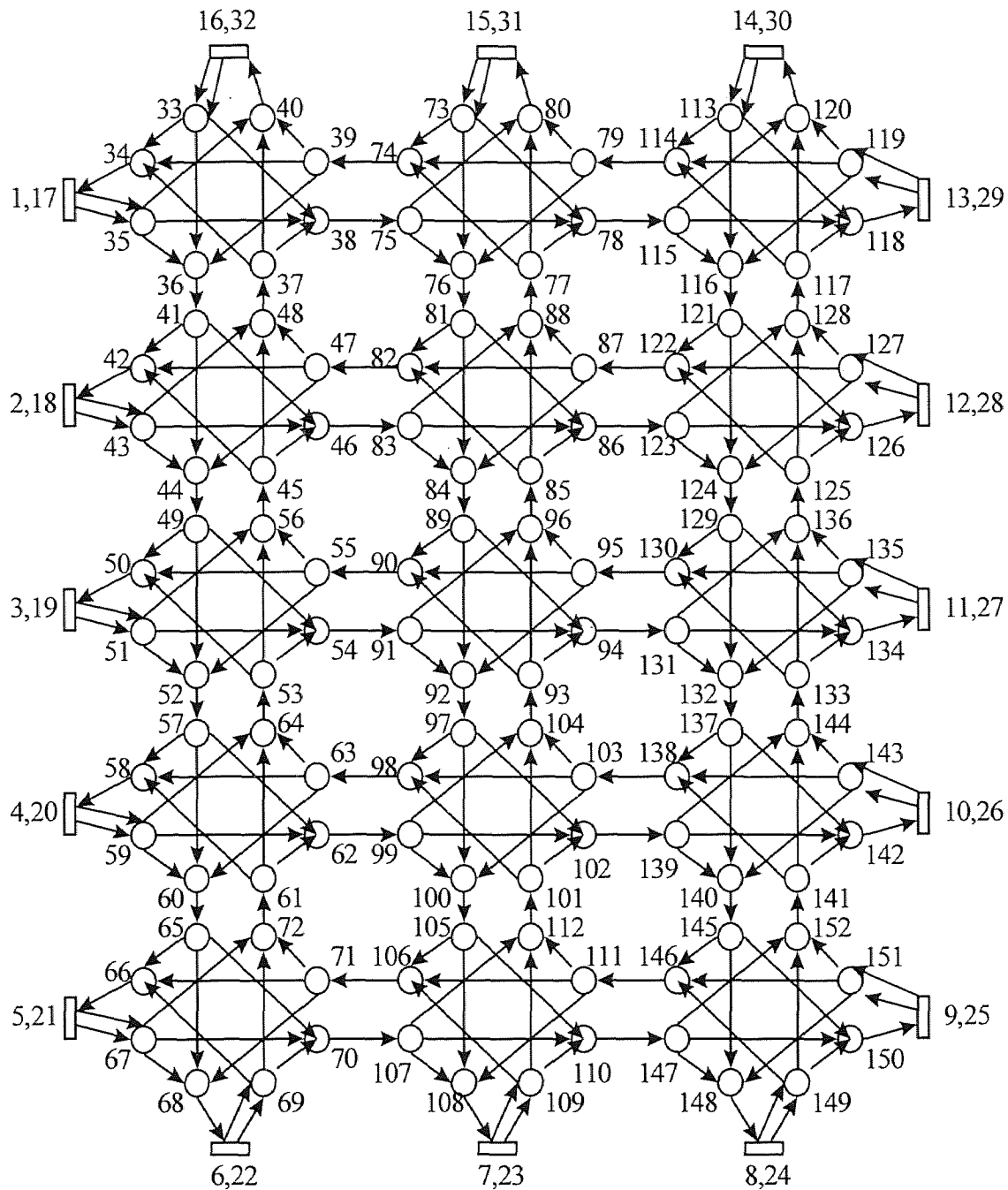
**Figure 5.1** Test Network 1 (3 by 3 grid network)



**Figure 5.2** Test Network 2 (3 by 4 grid network)



**Figure 5.3** Test Network 3 (6-intersection arterial)



**Figure 5.4** Test Network 4 (3 by 5 grid network)

The Origin-Destination (O-D) matrices used in the analysis of the UTNDP for each network are presented next.

### 5.1.2 O-D Trip Tables

Network 1: The O-D matrix of network 1 (Table 5.1), has 12 O-D pairs ranging from 160 to 480 trips per hour per O-D pair. The total volume in network 1 is 4800 trips per hour.

Network 2: The O-D matrix of network 2 (Table 5.2), has 42 O-D pairs ranging from 120 to 360 trips per hour per O-D pair. The total travel demand in network 2 is 8880 trips per hour.

Network 3: The O-D matrix of network 3 (Table 5.3), has 182 O-D pairs ranging from 20 to 100 trips per hour per O-D pair. The total travel demand in network 3 is 6770 trips per hour.

Network 4: The O-D matrix of network 4 (Table 5.4), has 240 O-D pairs ranging from 30 to 90 trips per hour per O-D pair. The total travel demand in network 4 is 11385 trips per hour.

**Table 5.1** Network 1 O-D Trips (Veh. /hour)

| O-D (veh./hour) | 1   | 2   | 3   | 4   |
|-----------------|-----|-----|-----|-----|
| 1               | --- | 480 | 720 | 480 |
| 2               | 320 | --- | 160 | 320 |
| 3               | 720 | 400 | --- | 400 |
| 4               | 160 | 320 | 320 | --- |

**Table 5.2** Network 2 O-D Trips (Veh. /hour)

| O-D (veh./hour) | 1   | 2   | 3   | 4   | 5   | 6   | 7   |
|-----------------|-----|-----|-----|-----|-----|-----|-----|
| 1               | --- | 120 | 360 | 360 | 240 | 120 | 240 |
| 2               | 240 | --- | 240 | 360 | 240 | 360 | 120 |
| 3               | 120 | 120 | --- | 240 | 240 | 360 | 120 |
| 4               | 360 | 360 | 240 | --- | 120 | 240 | 120 |
| 5               | 120 | 120 | 240 | 360 | --- | 240 | 120 |
| 6               | 240 | 240 | 240 | 240 | 120 | --- | 240 |
| 7               | 120 | 120 | 120 | 120 | 120 | 120 | --- |

**Table 5.3** Network 3 O-D Trips (Veh. /hour)

| O-D (veh./hour) | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  | 13  | 14  |
|-----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 1               | --- | 20  | 40  | 40  | 40  | 20  | 20  | 60  | 20  | 40  | 20  | 40  | 20  | 40  |
| 2               | 40  | --- | 20  | 20  | 20  | 60  | 40  | 20  | 20  | 40  | 30  | 50  | 30  | 80  |
| 3               | 20  | 40  | --- | 40  | 20  | 20  | 20  | 20  | 40  | 60  | 40  | 20  | 80  | 20  |
| 4               | 40  | 20  | 60  | --- | 40  | 40  | 40  | 20  | 60  | 40  | 60  | 60  | 40  | 20  |
| 5               | 40  | 20  | 40  | 60  | --- | 40  | 20  | 60  | 40  | 20  | 60  | 60  | 40  | 60  |
| 6               | 20  | 20  | 60  | 40  | 20  | --- | 20  | 40  | 40  | 60  | 40  | 20  | 40  | 60  |
| 7               | 20  | 20  | 20  | 20  | 20  | 20  | --- | 40  | 20  | 40  | 20  | 40  | 20  | 40  |
| 8               | 60  | 60  | 20  | 40  | 40  | 40  | 20  | --- | 60  | 40  | 60  | 60  | 20  | 40  |
| 9               | 40  | 60  | 20  | 20  | 20  | 40  | 40  | 40  | --- | 40  | 60  | 20  | 60  | 20  |
| 10              | 40  | 60  | 40  | 60  | 20  | 20  | 40  | 20  | 40  | --- | 60  | 40  | 40  | 20  |
| 11              | 60  | 20  | 20  | 20  | 20  | 20  | 40  | 20  | 40  | 20  | --- | 40  | 20  | 40  |
| 12              | 20  | 40  | 40  | 40  | 20  | 20  | 100 | 20  | 40  | 20  | 40  | --- | 20  | 40  |
| 13              | 60  | 40  | 40  | 60  | 20  | 60  | 60  | 40  | 40  | 60  | 40  | 60  | --- | 40  |
| 14              | 20  | 40  | 40  | 60  | 40  | 60  | 40  | 40  | 60  | 20  | 40  | 20  | 40  | --- |

**Table 5.4** Network 4 O-D Trips (Veh. /hour)

| O-D (veh./hour) | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  | 13  | 14  | 15  | 16  |
|-----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 1               | --- | 30  | 30  | 45  | 45  | 45  | 60  | 45  | 60  | 45  | 45  | 45  | 30  | 30  | 30  | 30  |
| 2               | 30  | --- | 30  | 45  | 45  | 45  | 45  | 45  | 45  | 45  | 45  | 45  | 30  | 30  | 30  | 30  |
| 3               | 75  | 75  | --- | 75  | 75  | 75  | 90  | 90  | 90  | 90  | 75  | 75  | 75  | 75  | 60  | 75  |
| 4               | 45  | 30  | 30  | --- | 30  | 30  | 45  | 45  | 45  | 45  | 45  | 45  | 45  | 45  | 45  | 45  |
| 5               | 45  | 45  | 30  | 30  | --- | 30  | 30  | 45  | 45  | 45  | 45  | 45  | 45  | 45  | 45  | 45  |
| 6               | 45  | 45  | 45  | 30  | 30  | --- | 30  | 30  | 45  | 30  | 30  | 45  | 45  | 45  | 45  | 30  |
| 7               | 90  | 75  | 90  | 90  | 90  | 75  | --- | 75  | 75  | 90  | 90  | 75  | 75  | 75  | 75  | 75  |
| 8               | 30  | 45  | 45  | 45  | 30  | 45  | 30  | --- | 30  | 30  | 30  | 30  | 45  | 45  | 45  | 45  |
| 9               | 45  | 45  | 45  | 45  | 45  | 45  | 45  | 30  | --- | 30  | 45  | 45  | 45  | 45  | 45  | 45  |
| 10              | 45  | 45  | 45  | 45  | 45  | 45  | 45  | 45  | 30  | --- | 30  | 45  | 30  | 45  | 45  | 45  |
| 11              | 90  | 90  | 75  | 90  | 75  | 90  | 75  | 90  | 90  | 75  | --- | 75  | 75  | 90  | 75  | 75  |
| 12              | 45  | 45  | 45  | 45  | 45  | 45  | 45  | 45  | 30  | 30  | 30  | --- | 45  | 30  | 30  | 30  |
| 13              | 30  | 30  | 30  | 30  | 45  | 45  | 45  | 45  | 45  | 45  | 45  | 30  | --- | 30  | 45  | 45  |
| 14              | 30  | 45  | 45  | 45  | 30  | 45  | 45  | 45  | 45  | 45  | 45  | 45  | 30  | --- | 30  | 30  |
| 15              | 75  | 45  | 90  | 90  | 90  | 90  | 90  | 90  | 90  | 90  | 90  | 90  | 90  | 60  | --- | 60  |
| 16              | 30  | 30  | 45  | 45  | 45  | 45  | 45  | 45  | 45  | 45  | 45  | 45  | 45  | 30  | 30  | --- |

## 5.2 Description of Tests Conducted

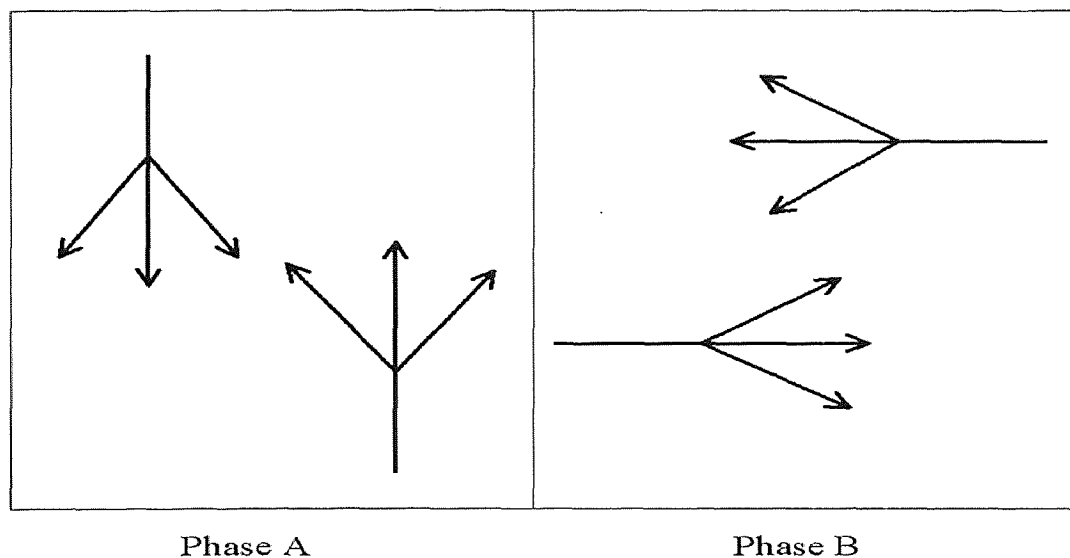
This section provides a description of the test runs of network 4, including the assumptions of intersection geometric layouts, signal plans, and network traffic characteristics.



The complexities of both the formulation and solution search procedure of a bi-level mixed integer nonlinear programming UTNDP make it difficult to enable the model to cover every aspect and detail of real world traffic engineering practice. This is especially true when either the intersection geometric layout, or the signal setting plan, or the traffic characteristic are atypical. Assumptions have to be made, and these assumptions are described next.

Intersections of test network 4 are assumed to be typical 4-leg signalized intersections with 2 lanes in each direction. For unsignalized intersections, the traffic control devices, such as the STOP sign, and the drivers' behavior are significantly different from signalized intersections. Therefore, the delays at unsignalized intersections are different from signalized intersections, and the link performance function used to estimate delay is different too. Berka et al. (13) addressed the estimation of delays at unsignalized intersections. With similar modifications, the UTNDP model can be extended to cover networks with unsignalized intersections using the methodology proposed by Berka (13). For non-4-leg intersections, they could be T type 3-leg intersections or intersections with more than four approaches. The network structure would be different if these types of intersections are included in the UTNDP model. The conflicting turning movements would be more complicated than the pair of conflicting movement (the left turn movement and the opposite through movement) considered in the UTNDP model, and therefore, the streamlined diagonalization step would have to be modified to cover these types of intersections.

One of the most important aspects of signal setting is the development of an appropriate phase plan. Unfortunately, there is no close-formed mathematical approach to determine phase plans, and professional judgement is needed in phase design. The key issue of developing a phase plan is how left turn movements are treated. When no left turn movements are protected, the phase plan is a simple, the most commonly used, two-phase plan is shown in Figure 5.5.



**Figure 5.5** A Two-Phase Signal Plan

When left turn movements are protected, exclusive left turn phases are often provided, either in the form of a three-phase plan, or a four-phase plan, or a protected plus permitted phase plan. The exclusive left turn phase can be split into leading or lagging green phases, especially when the two opposite left turn volumes are significantly different. The inclusion of more phases would have made the UTNDP more comprehensive. However, at the same time, it would have increased the computational complexity of the problem by several orders of magnitude. If a maximum of eight phases is used, then at each iteration and for each intersection, eight different phase plans would

have to be examined, implying a potential combination of  $8^n$  phase plans, where  $n$  is the number of intersections. To reduce the complexity of the study, only a two-phase plan is considered in the UTNDP model.

In a two-phase plan, all left and right turn movements are made on a permitted basis. The right turn movement usually is made from a shared lane with the through movement. The left turn movement could be made from either a shared lane or a separate lane, depending on the amount of traffic on both the subject left turn movement and the opposite through movement. The designation of lane groups in the UTNDP follows the 1997 HCM (46) procedure, which is presented in Figure 3.4. The right turn movement is always considered to share the right lane with the through movement, and right turn on red is not permitted.

Under this UTNDP, the travelers are assumed to have the freedom of making route choices, therefore the final flow pattern on the network should follow the user equilibrium (UE) condition. All the O-D demands and link flows are assumed to have been converted to standard passenger car flows. The ideal saturation flow rate per lane is assumed to be 1900 pcphgpl. In the saturation flow estimation procedure, adjustment factors for lane width, heavy vehicles in the traffic stream, existence of parking lane adjacent to the lane group, blocking effect of local buses and area type are assumed to be 1.0.

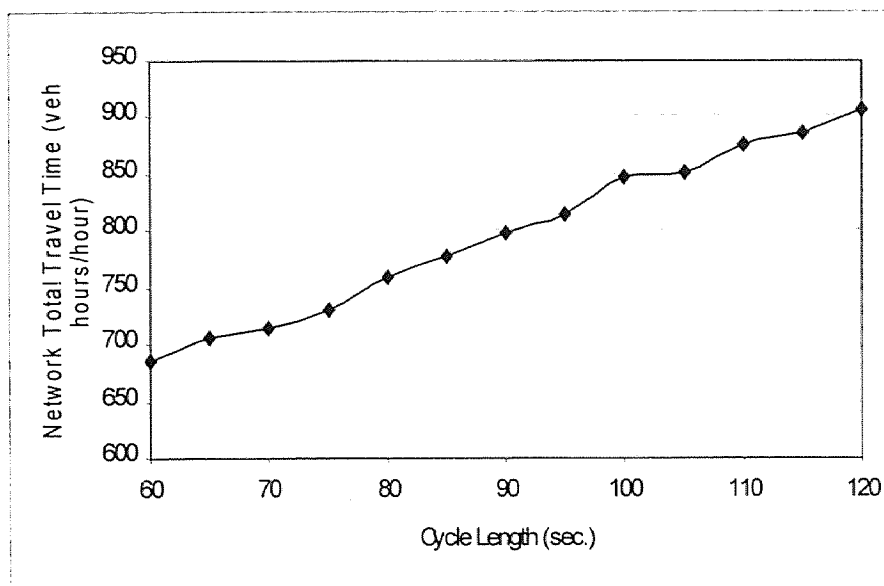
The next section presents the results of the UTNDP tested on network 4, based on the above mentioned network configuration, O-D demands, and assumptions.

### **5.3 Traffic Assignment/Traffic Control Results**

The first part of this section presents the impact of cycle length on traffic performance, where the best cycle length is chosen and used in the subsequent tests conducted. The second part studies the results in terms of traffic performance, including a summary of the UTNDP results, network-wide performance analysis and intersection-based performance analysis. The last part of this section presents the signal performance analysis, including a summary of signal setting results and a bandwidth analysis for 3 major arterials of network 4. Network 4 is used in this section as the base for the traffic engineering analysis due to its relatively larger size in comparison to the other three networks.

#### **5.3.1 Impact of Cycle Length on Network Total Travel Time**

In most urban signalized networks, the same cycle length is usually assigned to all intersections of the same network to achieve better synchronization of the traffic signals and the traffic movements. The most commonly used cycle length in urban signalized networks ranges from 60 to 120 seconds. In this study, network 4 is solved repeatedly with cycle lengths from 60 to 120 seconds at 5-second increments to locate the best cycle length. Figure 5.6 presents the user equilibrium (UE) network total travel time for a fixed level of demand at different cycle lengths.



**Figure 5.6** UE Network Total Travel Time VS. Cycle Length (Test Network 4)

As seen from the above figure, the UE network total travel time increases steadily with increases in the cycle length. The network total travel time increases from 687 to 906 Veh.-hours when cycle length increases from 60 seconds to 120 seconds, a 32% increase. For most of the links in this 3 by 5 grid network, the v/c ratios are less than 1.0, and the whole network can be considered as under-congested. For under-congested networks, the longer the cycle length is, the less portion of green is used by traffic flow, and therefore the total network travel time increases. For network 4, the optimal cycle length is 60 seconds, which is applicable to all intersections in the network. It is noted that shorter cycle lengths could produce better results. However, since some of the lane groups started producing v/c ratios greater than 1.2, then the total UE network total travel time would have been incorrect, since the 1994 HCM delay formula was calibrated for v/c ratios up to 1.2.

### 5.3.2 Traffic Performance

The study of traffic performance is divided into four major sections. The first section summarizes the traffic assignment results and the optimal traffic control strategies, including optimal left turn controls and lane designation controls. The second section presents the network-wide traffic performance measures that describe the average performance of an O-D pair of the network. The third section studies the travel speed on each link, which is the intuitive measurement of traffic performance of individual links. The last section studies the performance of each intersection based on the LOS and v/c ratio criteria. Intersection performance is important not only because a significant portion of travel time in an urban network is spent on waiting for green signals, but also because it reflects the efficiency of traffic control strategies, such as signal settings and left turn controls, which are the major concerns of this study. To demonstrate the effectiveness of traffic control strategy optimizations, the results under the original traffic, signal and network configuration condition (the original condition) before optimization are also presented parallel to the results under the optimized traffic, signal and network configuration condition (the final condition) in Table A.

To study the effectiveness of the UTNDP model under different O-D demand levels, the program was also run at 10% and 50% of the original O-D matrix. The 10% original O-D demand condition represents a near free flow condition because the O-D demands are very light, ranging from 3 to 9 vehs./hour. The 50% original O-D demand condition represents a less congested condition compared with the original O-D demand condition. The results under these three O-D plans are presented in Table B in Appendix B.

### 5.3.2.1 Summary of Traffic Assignment Results and Optimal Traffic Control

**Strategies:** Based on the given O-D matrix and the network 4 configuration, the UTNDP was solved using the SA-TABU search procedure. The results include the optimal intersection turning movement control that governs where left turn movements should be prohibited, the optimal lane designation scheme which dictates in which direction of a link an additional lane is needed to accommodate peak traffic flows, and the optimal link flows which are assigned to the network based on the optimal network configuration. The results are summarized in in Table A Appendix A. Column two of Table A shows the average link flows that represent the UE link flow pattern, and column three presents corresponding average link delay for each link of the network. Left turns could either be permitted or prohibited to eliminate conflicting flows, and potentially reduce the network UE total travel time. The number of lanes in the original network is always 2, while in the final network, the number of lanes on some links could increase from 2 to 3 or decrease from 2 to 1. The link v/c ratios are also shown in Appendix A, as an index of link congestion.

As seen in Table A in Appendix A, under the final condition, the average movement based delays occurred at intersections range from 3.9 sec./veh. to 168.1 sec./veh. Most of the large delays are experienced by left turn movements, such as left turn movement (133-130), (141-138), (53-50), (145-150) and (121-126), which are larger than 60 seconds per vehicle. These large left turn delays 'force' the travelers to choose another path to go to their destinations. For example, for a traveler who needs to make a left turn via link (133-130), s/he would rather go through via (133-136) whose delay of

18.6 sec./veh., is much less than the delay on left turn link (133-130), which is 168.1 sec./veh. The traveler will then make a left turn at the next intersection and then loop around to his/her destination, if necessary. The large delays at the left turn links are primarily due to the heavy conflicting traffic on opposite through links. Heavy conflicting flows make it difficult for left turn vehicles to find acceptable gaps to complete the turn, and therefore increases their delays. For example, links (133-130) and (141-138), which have the highest average delays, conflict with heavy opposite through flows, 1156 and 1214 vph on links (129-132) and (137-140), respectively.

Left turn movements from node 65 to 70, 97 to 102, 105 to 110 are prohibited. The number of lanes of link (100-105) is reduced from 2 lanes to 1 lane, while the opposite link (112-101) increases from 2 lanes to 3 lanes. Since link (100-105) only has 1 lane, left turn vehicles will block the through and right turn vehicles behind them if the left turn movement is permitted on the link, and the delay of both the left turn vehicles and the through and right turn vehicles will increase significantly. In the UTNDP model, the permission/prohibition of left turn movement at an intersection is based primarily on the delay and v/c ratio of the subject link and its relevant links. If a left turn movement is allowed on link (100-105), the delay and v/c ratio on link (100-105) increase significantly, and thus link (100-105) becomes an appropriate candidate for left turn prohibition. This observation reflects an important feature of the UTNDP that every single link in a network is not an isolated individual link but a member of a number of paths. The number of lanes on link (112-101) is increased from 2 lanes to 3 lane because the HEF value of link (112-101) is large. The large HEF value of link (112-101) is caused by the heavy traffic flow on the link (1401 vph), as opposed to the much lighter



traffic flow on the opposite link (100-105) (825 vph). Re-designation of the number of lanes on this link can better accommodate traffic in the peak direction, and thus reduce the network-wide travel time.

Volume to capacity ratio of a link is another important index of traffic. In the test network, v/c ratios are calculated for all regular links, and the results are summarized in Appendix A in Table A. Links (52-57), (100-105) and (132-137) exhibit v/c ratios greater than 1.0. Consistently, large average travel times are found on links (52-57) and (132-137). Among all the regular links, links (132-137) and (52-57) have the largest average travel times, 64.3 and 63.1 sec./veh., respectively. Although link (100-105) has high v/c ratio, the corresponding travel time on it is not as large, because the traffic flow is only 825 vph. The higher v/c ratio is caused by the reduction of 1 lane from link (100-105).

The total network travel time of network 4 has been reduced from 708.7 veh.-hours under the original condition to 686.8 veh.-hours under the final condition, a 3.1% decrease (see Table 5.6). The v/c ratios have been reduced on 23 of the regular links, increased on 20 links, and unchanged on 1 link. The number of over congested regular links with v/c ratios greater than 1.0 has been reduced from 4 under the original condition to 3 under the final condition.

The traffic assignment and traffic control optimization results under the three O-D plans are presented in Table B in Appendix B.

The v/c ratios have been reduced significantly with the decrease in the O-D demand. The O-D ratios ranges from 0.01 to 0.18, and from 0.19 to 0.66 for the case of 10% and 50% of the original O-D demands, respectively, as opposed to from 0.38 to 1.13

for the case of the original O-D demands. An interesting observation is that, even for light traffic conditions such as O-D plans 2 and 3, the implementation of appropriate traffic control strategies can improve transportation network performance as well as in heavy traffic conditions. Under O-D plan 3 ( $0.10 \times$  original O-D), the network 4 performance can be improved by prohibiting left turn movements on link (131-136), while under O-D plan 2 ( $0.50 \times$  original O-D), the network 4 performance can be improved by prohibiting left turn movements on links (49-54) and (65-70). The impact of O-D demands on delays under the three O-D demand levels is summarized in Table 5.5.

**Table 5.5** Average Delay by Turning Movement and O-D Conditions

|  |                         | O-D Plan 1<br>(Original) | O-D Plan 2 (50%<br>Original) | Change<br>(Plan 2-<br>Plan1) (%) | O-D Plan 3 (10%<br>Original) | Change<br>(Plan 3-<br>Plan1) (%) |
|--|-------------------------|--------------------------|------------------------------|----------------------------------|------------------------------|----------------------------------|
| Avg. Travel Time On<br>Regular Links (Sec.)    |                         | 38.39                    | 37.12                        | -3.3                             | 36.22                        | -5.7                             |
| Avg. Delay on<br>Intersections<br>Links (Sec.) | Rt. Turn &<br>Thru Mvt. | 11.93                    | 9.88                         | -17.2                            | 8.50                         | -28.8                            |
|  | Left Turn<br>Mvt.       | 36.23                    | 17.37                        | -52.1                            | 10.89                        | -69.9                            |

The degree of reduction on the average delays/travel times caused by the decrease of O-D demands is significantly different. The changes with respect to the travel time on regular links are small, 5.7% and 3.3% for the case of 10% and 50% of the original demands, respectively. This is because the cruising time of a vehicle between intersections is not very sensitive to the traffic volume on the subject link. However, for turning movements, especially left turns, the average delays are reduced significantly, 69.9% and 52.1% for the case of 10% and 50% of the original demands, respectively. This is because left turn movement delays are highly dependent on the conflicting

opposite through traffic flows, and any increases in the through volumes will increase the delay of conflicting left turn movements significantly.

**5.3.2.2 Network-Wide Traffic Performance:** The three network-wide traffic performance measures used in this section are average travel distance, average travel time, and average speed, which are defined in the following equations:

$$l = \frac{1}{F} \sum_i l_i f_i \quad (5-1)$$

where:

$l$  : average travel distance (miles);

$F$  : total number of trips per hour (vph);

$l_i$  : length of the link  $i$  (miles);

$f_i$  : flow on link  $i$  (vph).

$$t = \frac{1}{F} \sum_i t_i f_i \quad (5-2)$$

where:

$t$  : average travel time (minutes);

$t_i$  : travel time on the link  $i$  (minutes);

$$s = l/t \quad (5-3)$$

where:

$s$  : space mean speed (mph).

Average travel distance, average travel time and space mean speed are calculated for network 4, and the results are summarized in Table 5.6 below.

**Table 5.6** Network-Wide Measures of Test Network 4 (Cycle Length 60 Seconds)

| Measure                         | Original      | Final         | Difference (%)<br>(Final-Original) |
|---------------------------------|---------------|---------------|------------------------------------|
| Average travel distance (miles) | 0.77          | 0.77          | 0.0                                |
| Average travel time (minutes)   | 3 min. 5 sec. | 3 min. 1 sec. | -2.2                               |
| Average mean speed (mph)        | 15.0          | 15.3          | 2.0                                |
| Total travel time (Veh.-hours)  | 708.7         | 686.8         | -3.1                               |

The average travel distance is determined by how traffic demand is assigned on the network. In network 4, the average travel distance is 0.77 miles under the final traffic, signal and network configuration condition. The expected travel time of each O-D pair in the network is 3 minutes and 1 seconds, which includes the time spent on traveling between intersections and the delay at intersections, while the network-wide average speed is 15.3 mph. Compared with the original traffic, signal and network configuration condition, all the three measures (average travel time, average mean speed and network total travel time) under the final condition, have been improved.

The network-wide traffic performances under the three O-D plans are presented in Table 5.7 below:

**Table 5.7** Network-Wide Measures of Test Network 4 (Cycle Length 60 Seconds)  
Under Three O-D plans

| Measure                         | O-D Plan 1<br>(Original) | O-D Plan 2 (50%) | O-D Plan 3 (10%) |
|---------------------------------|--------------------------|------------------|------------------|
| Average travel distance (miles) | 0.77                     | 0.77             | 0.77             |
| Average travel time (minutes)   | 3 min. 1 sec.            | 2 min. 37 sec.   | 2 min. 25 sec.   |
| Average mean speed (mph)        | 15.3                     | 17.6             | 19.1             |
| Total travel time (Veh.-hours)  | 686.8                    | 305.9            | 56.9             |

The average travel distance remains the same for all the three O-D plans, while the other three measures vary significantly. As the O-D demands decrease from the original demand to 10% and then to 50% of the original demands, the average travel time decreases as well, from 3 minutes 1 second to 2 minutes 37 seconds and then to 2 minutes 25 seconds. In the mean time, the average mean speed increases from 15.3 mph to 17.6 (0.5 × O-D) mph and then to 19.1 (0.1 × O-D) mph. The total network travel time has been changed even more significantly, from 686.8 veh.-hours to 305.9 veh.-hours and then to 56.9 veh.-hours. This is caused by the reduction in O-D demand, which consequently reduces the average travel time of an individual vehicle.

**5.3.2.3 Link Travel Speeds:** As a major network-wide performance indicator, travel speed can be studied in depth by investigating the spatial distributions of link travel speeds. For regular links, travel time is computed as the cruise time plus the corresponding through movement delay, and travel speed is then computed using the link length and the calculated travel time. The results for the link travel speeds are summarized in Table 5.8. The link space mean speeds under the three O-D plans are presented in Table 5.9.

**Table 5.8** Link Space Mean Speeds of Test Network 4 (Cycle Length 60 Seconds)

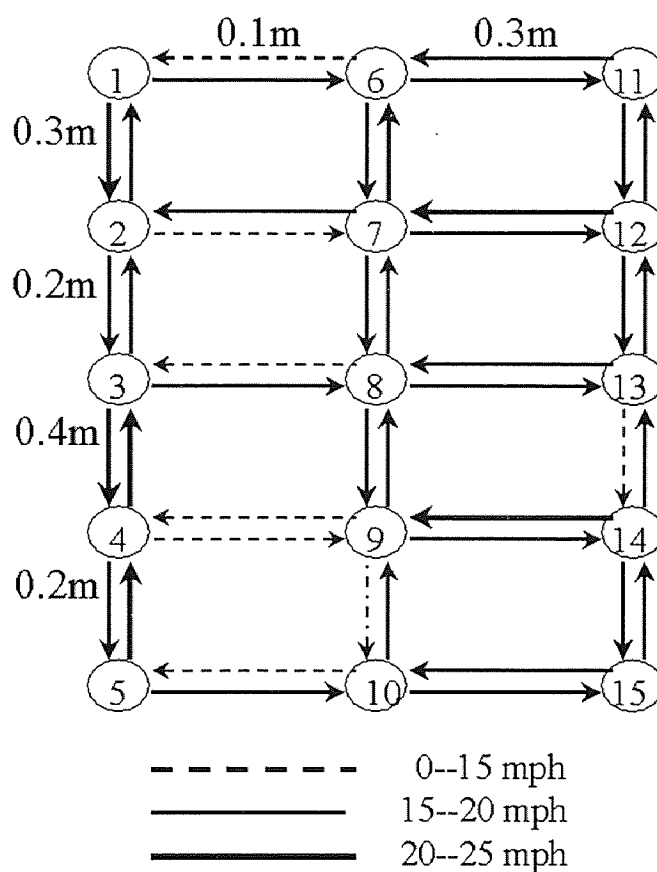
| Node     |        | Link Length | Link Space Mean Speed (mph) |       |
|----------|--------|-------------|-----------------------------|-------|
| Starting | Ending | (mi)        | Original                    | Final |
| 36       | 41     | 0.3         | 18.9                        | 20.1  |
| 38       | 75     | 0.1         | 16.8                        | 16.7  |
| 44       | 49     | 0.2         | 15.5                        | 17.4  |
| 46       | 83     | 0.1         | 12.8                        | 13.2  |
| 48       | 37     | 0.3         | 19.3                        | 17.7  |
| 52       | 57     | 0.4         | 16.9                        | 20.1  |
| 54       | 91     | 0.1         | 16.2                        | 14.6  |
| 56       | 45     | 0.2         | 11.9                        | 16.2  |
| 60       | 65     | 0.2         | 15.3                        | 16.6  |
| 62       | 99     | 0.1         | 13.3                        | 13.2  |
| 64       | 53     | 0.4         | 18.1                        | 20.1  |
| 70       | 107    | 0.1         | 15.3                        | 15.1  |
| 72       | 61     | 0.2         | 14.4                        | 20.9  |
| 74       | 39     | 0.1         | 9.0                         | 12.5  |
| 76       | 81     | 0.3         | 19.0                        | 19.1  |
| 78       | 115    | 0.3         | 19.1                        | 18.5  |
| 82       | 47     | 0.1         | 14.6                        | 17.4  |
| 84       | 89     | 0.2         | 18.1                        | 18.3  |
| 86       | 123    | 0.3         | 19.1                        | 18.7  |
| 88       | 77     | 0.3         | 18.9                        | 20.2  |
| 90       | 55     | 0.1         | 13.3                        | 13.8  |
| 92       | 97     | 0.4         | 18.3                        | 18.8  |
| 94       | 131    | 0.3         | 20.6                        | 20.3  |
| 96       | 85     | 0.2         | 17.5                        | 17.7  |
| 98       | 63     | 0.1         | 16.5                        | 14.1  |
| 100      | 105    | 0.2         | 18.0                        | 14.1  |
| 102      | 139    | 0.3         | 19.9                        | 19.0  |
| 104      | 93     | 0.4         | 17.2                        | 19.7  |
| 106      | 71     | 0.1         | 11.1                        | 10.7  |
| 110      | 147    | 0.3         | 18.2                        | 19.2  |
| 112      | 101    | 0.2         | 17.1                        | 18.4  |
| 114      | 79     | 0.3         | 17.5                        | 17.8  |
| 116      | 121    | 0.3         | 18.5                        | 18.3  |
| 122      | 87     | 0.3         | 20.2                        | 20.2  |
| 124      | 129    | 0.2         | 18.5                        | 17.6  |
| 128      | 117    | 0.3         | 19.7                        | 19.7  |
| 130      | 95     | 0.3         | 19.6                        | 18.4  |
| 132      | 137    | 0.4         | 14.9                        | 13.3  |
| 136      | 125    | 0.2         | 16.3                        | 17.3  |
| 138      | 103    | 0.3         | 20.5                        | 20.9  |
| 140      | 145    | 0.2         | 16.9                        | 15.7  |
| 144      | 133    | 0.4         | 17.9                        | 18.2  |
| 146      | 111    | 0.3         | 19.5                        | 18.7  |
| 152      | 141    | 0.2         | 17.6                        | 17.6  |

**Table 5.9 Link Space Mean Speeds of Test Network 4 (Cycle Length 60 Seconds)  
Under Three O-D Plans**

| Node     |        | Link Length | Link Space Mean Speed (mph) |                     |                     |
|----------|--------|-------------|-----------------------------|---------------------|---------------------|
| Starting | Ending | (mi)        | O-D Plan 1<br>(Original)    | O-D Plan 2<br>(50%) | O-D Plan 3<br>(10%) |
| 36       | 41     | 0.3         | 20.1                        | 21.5                | 21.9                |
| 38       | 75     | 0.1         | 16.7                        | 17.6                | 18.3                |
| 44       | 49     | 0.2         | 17.4                        | 18.0                | 20.1                |
| 46       | 83     | 0.1         | 13.2                        | 13.4                | 13.8                |
| 48       | 37     | 0.3         | 17.7                        | 19.7                | 20.4                |
| 52       | 57     | 0.4         | 20.1                        | 21.2                | 21.4                |
| 54       | 91     | 0.1         | 14.6                        | 17.1                | 18.2                |
| 56       | 45     | 0.2         | 16.2                        | 19.1                | 20.1                |
| 60       | 65     | 0.2         | 16.6                        | 19.3                | 22.0                |
| 62       | 99     | 0.1         | 13.2                        | 13.8                | 14.2                |
| 64       | 53     | 0.4         | 20.1                        | 19.5                | 20.7                |
| 70       | 107    | 0.1         | 15.1                        | 16.6                | 16.7                |
| 72       | 61     | 0.2         | 20.9                        | 20.4                | 21.7                |
| 74       | 39     | 0.1         | 12.5                        | 13.8                | 13.9                |
| 76       | 81     | 0.3         | 19.1                        | 19.4                | 19.8                |
| 78       | 115    | 0.3         | 18.5                        | 18.9                | 19.3                |
| 82       | 47     | 0.1         | 17.4                        | 16.7                | 17.5                |
| 84       | 89     | 0.2         | 18.3                        | 19.4                | 19.4                |
| 86       | 123    | 0.3         | 18.7                        | 19.4                | 20.0                |
| 88       | 77     | 0.3         | 20.2                        | 21.6                | 22.3                |
| 90       | 55     | 0.1         | 13.8                        | 13.4                | 14.0                |
| 92       | 97     | 0.4         | 18.8                        | 19.4                | 20.0                |
| 94       | 131    | 0.3         | 20.3                        | 21.3                | 21.6                |
| 96       | 85     | 0.2         | 17.7                        | 18.5                | 19.4                |
| 98       | 63     | 0.1         | 14.1                        | 16.7                | 16.7                |
| 100      | 105    | 0.2         | 14.1                        | 18.7                | 19.2                |
| 102      | 139    | 0.3         | 19.0                        | 19.4                | 20.0                |
| 104      | 93     | 0.4         | 19.7                        | 21.0                | 22.1                |
| 106      | 71     | 0.1         | 10.7                        | 15.9                | 15.9                |
| 110      | 147    | 0.3         | 19.2                        | 19.5                | 19.8                |
| 112      | 101    | 0.2         | 18.4                        | 18.3                | 19.1                |
| 114      | 79     | 0.3         | 17.8                        | 18.3                | 18.3                |
| 116      | 121    | 0.3         | 18.3                        | 18.6                | 20.3                |
| 122      | 87     | 0.3         | 20.2                        | 21.6                | 21.8                |
| 124      | 129    | 0.2         | 17.6                        | 18.5                | 19.5                |
| 128      | 117    | 0.3         | 19.7                        | 20.8                | 22.5                |
| 130      | 95     | 0.3         | 18.4                        | 19.6                | 19.7                |
| 132      | 137    | 0.4         | 13.3                        | 17.8                | 20.2                |
| 136      | 125    | 0.2         | 17.3                        | 18.4                | 19.3                |
| 138      | 103    | 0.3         | 20.9                        | 21.1                | 22.1                |
| 140      | 145    | 0.2         | 15.7                        | 18.2                | 19.6                |
| 144      | 133    | 0.4         | 18.2                        | 19.5                | 20.2                |
| 146      | 111    | 0.3         | 18.7                        | 19.7                | 20.5                |
| 152      | 141    | 0.2         | 17.6                        | 18.8                | 19.0                |

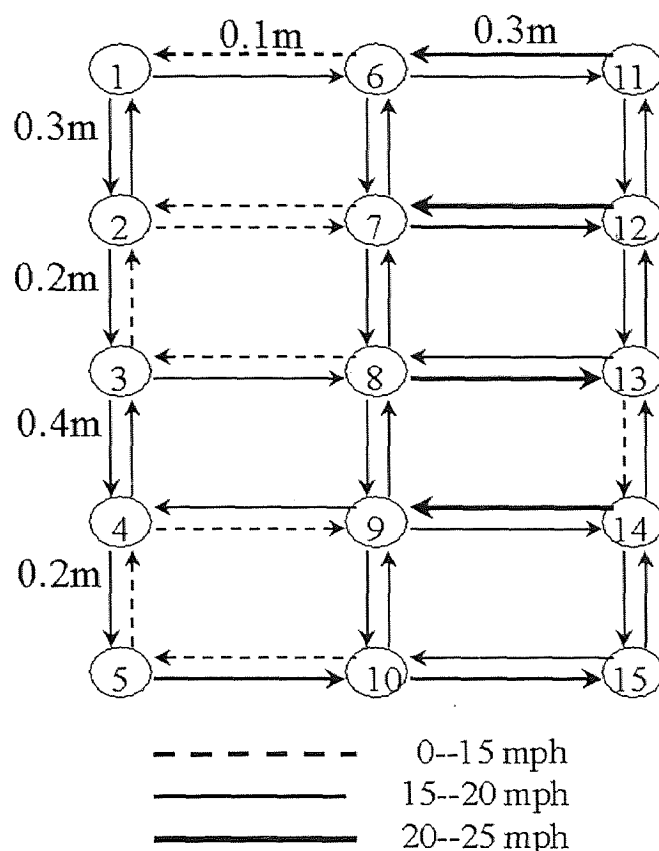
Compared with the original O-D demand matrix, link space mean speeds increased on 22 of the regular links, decreased on 19 links, and remained the same on 3 links, in the final condition. The network-wide space mean speed improved from 15.0 mph to 15.3 mph.

Link travel speeds are divided into 3 groups, below 15 mph, between 15 and 20 mph, and between 20 and 25 mph. Figures 5.7 and 5.8 depict the spatial distribution of link travel speeds of network 4 for the final and original conditions, respectively.



**Figure 5.7** Spatial Distribution of Link Space Mean Speeds for Network 4 (Cycle Length 60 Seconds) Under the Final Condition





**Figure 5.8** Spatial Distribution of Link Space Mean Speeds for Network 4 (Cycle Length 60 Seconds) Under the Original Condition

Under the final condition, out of the 44 regular links in the network, eight links have space mean speeds less than 15 mph; eight links have speeds greater than 20 mph, and the remaining 18 links have speeds ranging between 15 and 20 mph. Almost all of the low speed links are located on the left side of the network. This is because these links are relatively shorter and turning delays on these short links occupy a larger portion of travel times on these links. One exception is the slow speed from intersection 13 to 14, or on link (132-137) on the expanded network. The slow speed from intersection 13 to 14 is primarily due to the heavy traffic flow on it (1770vph).

**5.3.2.4 Intersection Performance:** Since a significant portion of the delay occurred at intersections, the performance of an intersection is of particular interest to this study. Intersection critical v/c ratio and level of service (LOS) are two major indicators of the overall performance of the intersection. The critical v/c ratio for the intersection is defined in terms of the critical lane groups:

$$X_C = \sum (v / s)_{ci} [C / (C - L)] \quad (5-4)$$

where:

$X_C$  : critical v/c ratio for the intersection;

$\sum (v / s)_{ci}$  : summation of flow ratios for all critical lane groups,  $i$  ;

$s$  : saturation flow;

$C$  : cycle length, sec.;

$L$  : total lost time per cycle.

Intersection critical v/c ratio  $X_C$  is a composite v/c for the sum of the critical lane groups within the intersection. If  $X_C$  exceeds 1.0, it indicates that either the signal settings or the lane designation at the intersection is inadequate for one or more lane groups. If  $X_C$  is less than 1.0, it indicates that the signal setting and lane designation are adequate to handle all critical flows without having demand exceeding capacity.

However, a  $X_C$  less than 1.0 does not guarantee that all the lane groups'  $X_C$  is less than 1.0. The calculation of  $X_C$  requires the identification of critical lane groups. For each phase, the lane group with the highest v/s ratio is the one that determines the amount of green time needs to be allocated to the phase, and it is considered as the critical lane

group of the subject phase. In this study, all signal settings are treated as non-overlapping, and there is one critical lane group for each signal phase.

The Level of Service of a signalized intersection is defined in terms of delay which is dependent on the signal settings (including offsets), implemented traffic control policies, traffic flows and network configuration. The delays experienced by different approaches leading to an intersection are obtained from the results of the UTNDP. The average intersection delay can be aggregated from approach delays, as shown in equation (5-5) below:

$$d_I = \frac{\sum d_A f_A}{\sum f_A} \quad (5-5)$$

where:

$d_I$  : average delay for intersection I,

$d_A$  : average delay on approach A,

$f_A$  : flow on approach A.

The criteria which determine the level of service of an intersection is given in 1997 HCM (46), which is shown in Table 5.10 below:

**Table 5.10** 1997 HCM Level of Service Table

| Level of Service (LOS) | Average Delay Per Vehicle (Sec./Veh.) |
|------------------------|---------------------------------------|
| A                      | $\leq 10.0$                           |
| B                      | $> 10.0$ and $\leq 20.0$              |
| C                      | $> 20.0$ and $\leq 35.0$              |
| D                      | $> 35.0$ and $\leq 55.0$              |
| E                      | $> 55.0$ and $\leq 80.0$              |
| F                      | $> 80.0$                              |

LOS F is considered unacceptable. Poor performance is often due to the combination of inadequate signal settings, traffic control policies, network configurations and large traffic flows. Long cycle lengths also lead to poor LOS.

The intersection critical v/c ratio, the average intersection delay per vehicle and LOS are calculated using the UTNDP results of network 4 and are summarized in Table 5.11. Under the final condition, 14 out of the 15 intersections have LOS B, and only one has LOS C. Originally, 12 intersections have LOS B and 3 intersections have LOS C. Most of the intersection v/c ratios of the 15 intersections is located in the range of 0.6 to 0.8, and this indicates the current traffic demands can be handled appropriately by the network. Comparing the results under the final conditions with the results under original conditions, the average intersection delays decreased at 11 intersections, increased at 4 intersections, while the LOS of 3 intersections were improved from C to B, and one deteriorated from B to C. However, network-wide improvements do not necessarily mean improvement at all intersections or lane groups or movements. As indicated while some components of the network improve their performance, other components see degradation in their performance.

The summary of intersection performances under the three O-D plans is presented in Table 5.12. As seen from Table 5.12, the average intersection delays decreased consistently across all the 15 intersections as the O-D demand decreased, while the critical v/c ratios decreased consistently as well. For the case of 10% of the original O-D demands, 10 out of 15 intersections have LOS A, while the other 5 are at the upper B level. For the case of 50% of the original O-D demands, 13 out of 15 intersections have LOS B, while the other 2 have LOS A.

**Table 5.11** Summary of Intersection Performances of Test Network 4 (Cycle Length 60 Seconds)

| Intersection | Critical Lane Group     |                         |                        |                        | Critical v/c Ratio |       | Average Intersection Delay (Sec./Veh.) |       | Level of Service (LOS) |       |
|--------------|-------------------------|-------------------------|------------------------|------------------------|--------------------|-------|--|-------|------------------------|-------|
|              | North-South             |                         | East-West              |                        | Original           | Final | Original                               | Final | Original               | Final |
|              | Original                | Final                   | Original               | Final                  |                    |       |  |       |                        |       |
| 1            | south                   | south through and right | east through and right | east                   | 0.76               | 0.63  | 20.7                                   | 18.5  | C                      | B     |
| 2            | south through and right | south through and right | east through and right | east                   | 0.81               | 0.65  | 20.7                                   | 14.3  | C                      | B     |
| 3            | north                   | north                   | west through and right | west through and right | 0.76               | 0.71  | 18.4                                   | 17.8  | B                      | B     |
| 4            | north                   | north                   | west left              | east through and right | 0.74               | 0.70  | 19.6                                   | 14.2  | B                      | B     |
| 5            | north                   | North                   | west left              | west left              | 0.84               | 0.61  | 21.7                                   | 17.1  | C                      | B     |
| 6            | south                   | South                   | east                   | west                   | 0.62               | 0.62  | 14.9                                   | 14.7  | B                      | B     |
| 7            | south                   | South                   | east                   | west                   | 0.61               | 0.66  | 13.9                                   | 13.7  | B                      | B     |
| 8            | south through and right | south                   | west                   | west through and right | 0.79               | 0.77  | 17.4                                   | 13.2  | B                      | B     |
| 9            | south                   | South                   | east                   | east                   | 0.58               | 0.50  | 14.2                                   | 13.3  | B                      | B     |
| 10           | south through and right | south through and right | west                   | west through and right | 0.62               | 0.72  | 15.2                                   | 16.9  | B                      | B     |
| 11           | south                   | South                   | west                   | west                   | 0.58               | 0.64  | 15.6                                   | 15.8  | B                      | B     |
| 12           | south                   | North                   | east through and right | west                   | 0.52               | 0.54  | 16.5                                   | 15.9  | B                      | B     |
| 13           | north                   | north                   | west                   | east through and right | 0.62               | 0.75  | 16.4                                   | 16.8  | B                      | B     |
| 14           | north through and right | north through and right | east through and right | east through and right | 0.71               | 0.75  | 19.4                                   | 15.7  | B                      | B     |
| 15           | north through and right | north left              | west                   | east through and right | 0.58               | 0.73  | 17.6                                   | 28.1  | B                      | C     |

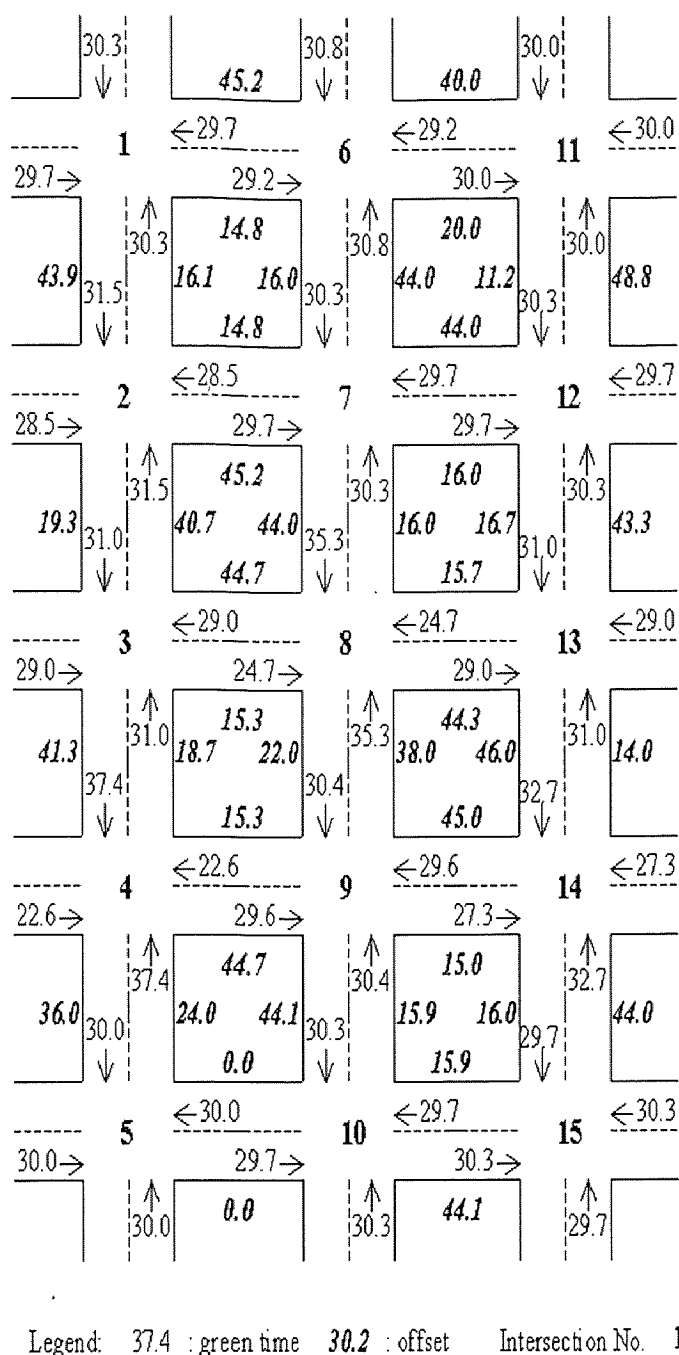
**Table 5.12** Summary of Intersection Performances of Test Network 4 (Cycle Length 60 Seconds) Under Three O-D Plans

| Intersection | O-D Plan 1 (Original) |               |       |           |     | O-D Plan 2 (50%) |               |       |           |     | O-D Plan 3 (10%) |               |       |           |     |
|--------------|-----------------------|---------------|-------|-----------|-----|------------------|---------------|-------|-----------|-----|------------------|---------------|-------|-----------|-----|
|              | Crit. Ln. Grp.        |               | Crit. | Avg.      | LOS | Crit. Ln. Grp.   |               | Crit. | Avg.      | LOS | Crit. Ln. Grp.   |               | Crit. | Avg.      | LOS |
|              | North-South           | East-West     | V/C   | Int. Del. |     | North-South      | East-West     | V/C   | Int. Del. |     | North-South      | East-West     | V/C   | Int. Del. |     |
| 1            | s. thr. & rt.         | east          | 0.63  | 18.5      | B   | south            | east          | 0.28  | 13.0      | B   | south            | west          | 0.06  | 11.3      | B   |
| 2            | s. thr. & rt.         | east          | 0.65  | 14.3      | B   | south            | e. thr. & rt. | 0.62  | 10.0      | B   | north            | east left     | 0.07  | 7.7       | A   |
| 3            | north                 | w. thr. & rt. | 0.71  | 17.8      | B   | south            | w. thr. & rt. | 0.46  | 13.3      | B   | north            | w. thr. & rt. | 0.10  | 10.3      | B   |
| 4            | north                 | e. thr. & rt. | 0.70  | 14.2      | B   | north            | e. thr. & rt. | 0.49  | 9.9       | A   | north            | east left     | 0.07  | 8.1       | A   |
| 5            | North                 | west left     | 0.61  | 17.1      | B   | north            | w. thr. & rt. | 0.31  | 10.1      | B   | north            | west left     | 0.09  | 8.0       | A   |
| 6            | South                 | west          | 0.62  | 14.7      | B   | n. thr. & rt.    | west          | 0.41  | 10.4      | B   | south            | west          | 0.06  | 8.5       | A   |
| 7            | South                 | west          | 0.66  | 13.7      | B   | south            | east          | 0.31  | 10.2      | B   | south            | east          | 0.07  | 8.7       | A   |
| 8            | south                 | w. thr. & rt. | 0.77  | 13.2      | B   | south            | west          | 0.39  | 9.4       | A   | south            | west          | 0.09  | 7.4       | A   |
| 9            | South                 | east          | 0.50  | 13.3      | B   | south            | east          | 0.30  | 10.5      | B   | south            | east          | 0.07  | 7.0       | A   |
| 10           | s. thr. & rt.         | w. thr. & rt. | 0.72  | 16.9      | B   | s. thr. & rt.    | east          | 0.37  | 11.7      | B   | s. thr. & rt.    | west          | 0.05  | 9.7       | A   |
| 11           | South                 | west          | 0.64  | 15.8      | B   | north            | e. thr. & rt. | 0.28  | 12.0      | B   | north            | east left     | 0.06  | 10.9      | B   |
| 12           | North                 | west          | 0.54  | 15.9      | B   | north            | e. thr. & rt. | 0.43  | 12.7      | B   | north            | east left     | 0.06  | 10.4      | B   |
| 13           | north                 | e. thr. & rt. | 0.75  | 16.8      | B   | north            | e. thr. & rt. | 0.45  | 12.3      | B   | south            | west          | 0.08  | 9.4       | A   |
| 14           | n. thr. & rt.         | e. thr. & rt. | 0.75  | 15.7      | B   | north            | e. thr. & rt. | 0.46  | 11.6      | B   | north            | e. thr. & rt. | 0.07  | 9.5       | A   |
| 15           | north left            | e. thr. & rt. | 0.73  | 28.1      | C   | north left       | west          | 0.40  | 13.1      | B   | north left       | e. thr. & rt. | 0.06  | 10.2      | B   |

### 5.3.3 Signal Performance Analysis

In urban transportation networks, signalized intersections are relatively closely spaced. Therefore, it is necessary to coordinate signals in order to preserve good traffic progression patterns. The coordination of signals is achieved by selecting appropriate green splits at intersections and reasonable offsets between adjacent intersections. The prime benefit of signal coordination is improvement of network-wide traffic performance by reducing the average delays and the number of stops per vehicle. The ideal condition is that vehicles are sent through a sequence of intersections without being stopped or delayed. However, this ideal condition can't be reached for all the streets in a network because of the competition of signal resources by vehicles on conflicting streets. In the UTNDP model, both green splits and offsets are considered as decision variables and optimized so as to minimize network total travel time. In the first part of this section, the signal setting results of network 4 are summarized. Then, the bandwidth of three major arterials in the network is calculated using the obtained green times and offsets. The impact of cycle length on network total travel time has already been presented in section 5.2.

**5.3.3.1 Summary of Signal Setting Results:** The green times at each intersection and the offsets between adjacent intersections are summarized in Tables 5.13 and 5.14, respectively. Green times and offsets are also illustrated in Figure 5.9.



**Figure 5.9** Signal Setting Results of Test Network 4 (Cycle Length 60 Seconds)



There are two major constraints that dictate the green splits and offset setting. First, green splits on each approach of an intersection should be long enough to accommodate the traffic in that direction. In other words, the traffic demand on an approach should not exceed the capacity allocated to the subject approach. The capacity of the approach is determined by green splits, and geometric and traffic characteristics. Second, the allocated green splits and offsets should satisfy the loop constraints. For example, on loop 3-8-9-4-3, the summation of green splits and offsets should be equal to the cycle length multiplied by an integer. In this case, the summation of green splits and offsets of loop 3-8-9-4-3 is 180 seconds ( $15.3+24.7+22.0+30.4+15.3+22.6+18.7+31.0$ ) or 3 cycle lengths.

**Table 5.13** Green Splits at Intersections of Test Network 4 (Cycle Length 60 Seconds)

| Intersection | Effective Green (North-South)<br>(Sec.) |       | Effective Green (East-West)<br>(Sec.) |       |
|--------------|---|-------|---------------------------------------|-------|
|              | Original                                | Final | Original                              | Final |
| 1            | 30.0                                    | 30.3  | 30.0                                  | 29.7  |
| 2            | 30.0                                    | 31.5  | 30.0                                  | 28.5  |
| 3            | 30.0                                    | 31.0  | 30.0                                  | 29.0  |
| 4            | 30.0                                    | 37.4  | 30.0                                  | 22.6  |
| 5            | 30.0                                    | 30.0  | 30.0                                  | 30.0  |
| 6            | 30.0                                    | 30.8  | 30.0                                  | 29.2  |
| 7            | 30.0                                    | 29.7  | 30.0                                  | 30.3  |
| 8            | 30.0                                    | 24.7  | 30.0                                  | 35.3  |
| 9            | 30.0                                    | 30.4  | 30.0                                  | 29.6  |
| 10           | 30.0                                    | 30.3  | 30.0                                  | 29.7  |
| 11           | 30.0                                    | 30.0  | 30.0                                  | 30.0  |
| 12           | 30.0                                    | 30.3  | 30.0                                  | 29.7  |
| 13           | 30.0                                    | 29.0  | 30.0                                  | 31.0  |
| 14           | 30.0                                    | 32.7  | 30.0                                  | 27.3  |
| 15           | 30.0                                    | 29.7  | 30.0                                  | 30.3  |

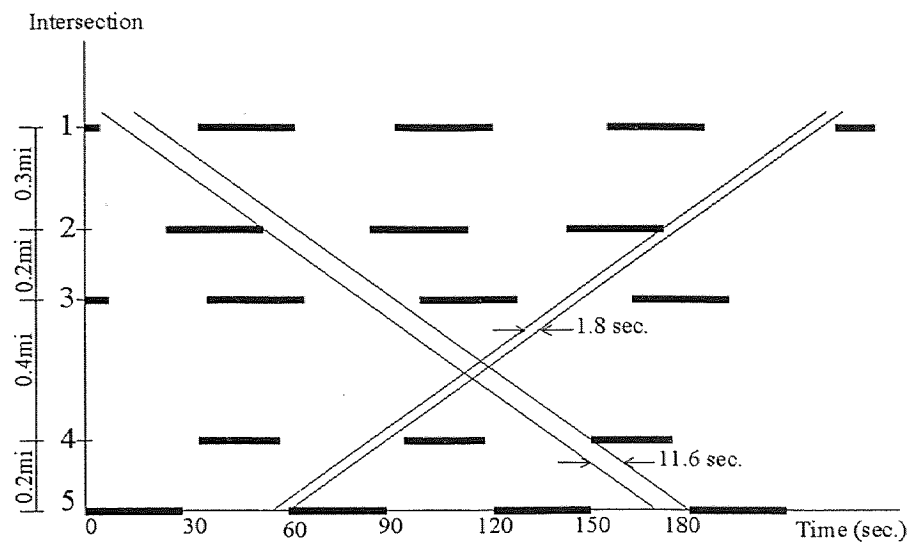
**Table 5.14** Offsets Between Adjacent Intersections of Test Network 4  
(Cycle Length 60 Seconds)

| Intersection |            | Offset (Sec.) |       |
|--------------|------------|---------------|-------|
| Upstream     | Downstream | Original      | Final |
| 1            | 2          | 45.0          | 43.9  |
| 1            | 6          | 15.0          | 14.8  |
| 2            | 1          | 15.0          | 16.1  |
| 2            | 3          | 15.0          | 19.3  |
| 2            | 7          | 45.0          | 45.2  |
| 3            | 2          | 45.0          | 40.7  |
| 3            | 4          | 45.0          | 41.3  |
| 3            | 8          | 15.0          | 15.3  |
| 4            | 3          | 15.0          | 18.7  |
| 4            | 5          | 15.0          | 36.0  |
| 4            | 9          | 45.0          | 44.7  |
| 5            | 4          | 45.0          | 24.0  |
| 5            | 10         | 15.0          | 0.0   |
| 6            | 1          | 45.0          | 45.2  |
| 6            | 7          | 15.0          | 16.0  |
| 6            | 11         | 15.0          | 20.0  |
| 7            | 2          | 15.0          | 14.8  |
| 7            | 6          | 45.0          | 44.0  |
| 7            | 8          | 45.0          | 44.0  |
| 7            | 12         | 15.0          | 16.0  |
| 8            | 3          | 45.0          | 44.7  |
| 8            | 7          | 15.0          | 16.0  |
| 8            | 9          | 15.0          | 22.0  |
| 8            | 13         | 45.0          | 44.3  |
| 9            | 4          | 15.0          | 15.3  |
| 9            | 8          | 45.0          | 38.0  |
| 9            | 10         | 45.0          | 44.1  |
| 9            | 14         | 15.0          | 15.0  |
| 10           | 5          | 45.0          | 0.0   |
| 10           | 9          | 15.0          | 15.9  |
| 10           | 15         | 15.0          | 44.1  |
| 11           | 6          | 45.0          | 40.0  |
| 11           | 12         | 15.0          | 11.2  |
| 12           | 7          | 45.0          | 44.0  |
| 12           | 11         | 45.0          | 48.8  |
| 12           | 13         | 15.0          | 16.7  |
| 13           | 8          | 15.0          | 15.7  |
| 13           | 12         | 45.0          | 43.3  |
| 13           | 14         | 45.0          | 46.0  |
| 14           | 9          | 45.0          | 45.0  |
| 14           | 13         | 15.0          | 14.0  |
| 14           | 15         | 15.0          | 16.0  |
| 15           | 10         | 45.0          | 15.9  |
| 15           | 14         | 45.0          | 44.0  |

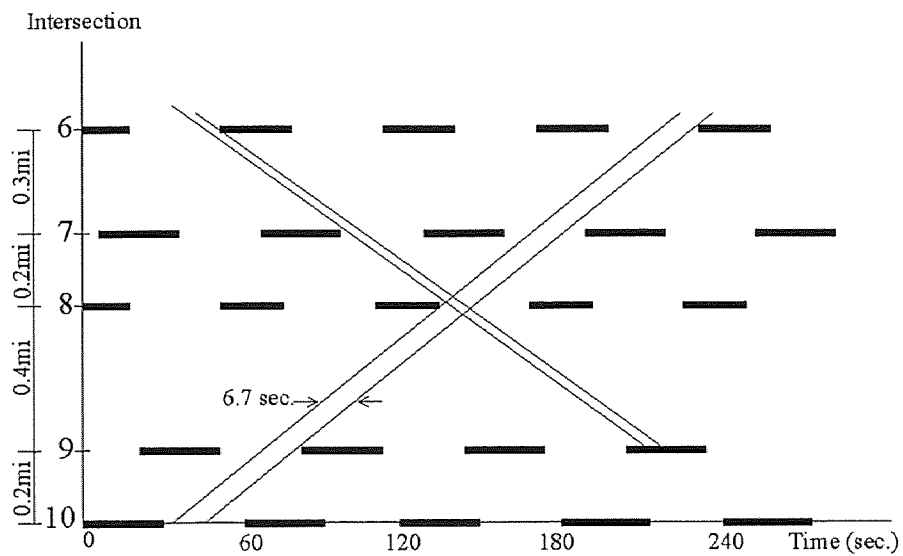
**5.3.3.2 Bandwidths of Three Major Arterials:** Bandwidth, which is often referred to as the window of green through which platoons of vehicles can move, is an important measure of signal efficiency of an arterial. Large bandwidth along an arterial reflects good traffic progression. However, for a coordinated transportation network, a large bandwidth in one direction of an arterial in the network is often selected by sacrificing the signal efficiency in the opposite direction or on the adjacent arterials and streets. For example, if the cross streets of the subject arterial have heavy traffic, the priority given to the arterial through the signal settings may actually increase the network-wide total travel time. Since the primary objective of this UTNDP model is the minimization of the network-wide total travel time rather than the maximization of bandwidth on a particular arterial, the bandwidth on some arterials in the network may not be optimal. The bandwidths for the 3 vertical (north-south) arterials of network 4 under the final condition are presented in Figures 5.10, 5.11, and 5.12, respectively. The bandwidth results under both the original and the final conditions are summarized in Table 5.15.

**Table 5.15** Bandwidth of 3 Major Arterials of Test Network 4

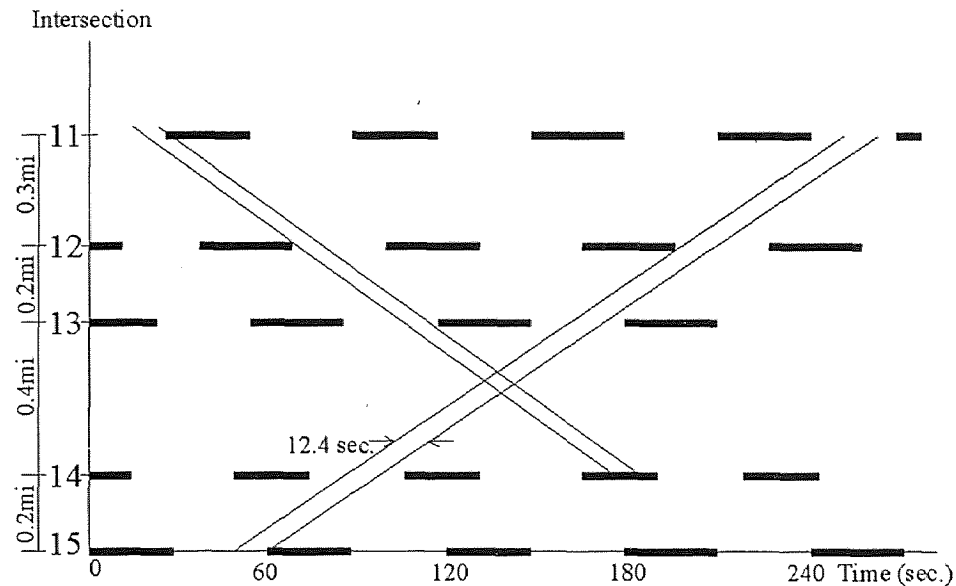
| Arterial | Direction                    | Bandwidth (sec.) |       | Average Flow (veh./hour) |       |
|----------|------------------------------|------------------|-------|--------------------------|-------|
|          |                              | Original         | Final | Original                 | Final |
| 1        | 1-2-3-4-5 (North-South)      | 0.0              | 11.6  | 1691                     | 1331  |
|          | 5-4-3-2-1 (South-North)      | 0.0              | 1.8   | 1063                     | 979   |
| 2        | 6-7-8-9-10 (North-South)     | 0.0              | 0.0   | 815                      | 843   |
|          | 10-9-8-7-6 (South-North)     | 3.6              | 6.7   | 1202                     | 1338  |
| 3        | 11-12-13-14-15 (North-South) | 0.0              | 0.0   | 1114                     | 1443  |
|          | 15-14-13-12-11 (South-North) | 0.0              | 12.4  | 1016                     | 964   |



**Figure 5.10** Time-Space Diagram of Arterial 1 of Test Network 4 (Cycle Length 60 Seconds) Under the Final Condition



**Figure 5.11** Time-Space Diagram of Arterial 2 of Test Network 4 (Cycle Length 60 Seconds) Under the Final Condition



**Figure 5.12** Time-Space Diagram of Arterial 3 of Test Network 4 (Cycle Length 60 Seconds) Under the Final Condition

Engineers usually wish to maximize bandwidth in the direction with heavy traffic, while the other direction is largely ignored. More commonly, the bandwidths in the two directions are designed to be in the same ratio as the flows in the two directions. Under the final condition, the average flows in the north-south direction of arterial 1 and south-north direction of arterial 2 are much heavier than the average flows in their opposite directions, thus signal setting priorities should be given to these two heavy traffic directions. Under the final condition, the bandwidths in the north-south direction of arterial 1 and south-north direction of arterial 2 are 11.6 and 6.7 seconds, respectively, as opposed to 1.8 and 0.0 seconds in the opposite directions. This is consistent with real world engineering practices. However, this observation doesn't hold for arterial 3. This might be due to the signal coordination constraints in a transportation network, such as

the loop constraints. The good signal progression on arterial 2 may lead to deteriorating signal progression on an adjacent arterial such as arterial 3. Comparing the bandwidths of the final and the original conditions, the bandwidths of the final condition are consistently better than those of the original condition.

## CHAPTER 6

### PERFORMANCE OF THE SA-TABU HEURISTIC

The four test networks were subjected to the application of the heuristic search strategy in solving the UTNDP. One of the most important elements of the SA-TABU search procedure is the HEF (see equation 3.27), which is also presented below.

Heuristic Evaluation Function (HEF):

$$HEF_i = a \times (V_i / C_i) + b \times HISCON_i + c \times RAND(0,1)$$

The HEF has three components, the link v/c ratio, the historical contribution factor, and the random factor. The link v/c ratio reflects the performance of traffic on the subject link under current solution set, the historical contribution factor reflects the accumulated contribution of the current move since the start of the heuristic search procedure, and the random factor is designed to enhance the stochastic nature of the search procedure.

#### 6.1 Summary of the Heuristic Search

Since the UTNDP solution procedure is a heuristic search procedure, the major parameters of this procedure are discussed in this section, as they have significant impact on the results. The three major types of parameters are: TABU list length, control parameter (temperature) decreasing rate and Markov chain length, and the weight coefficients of the three components of the HEF, namely the current link v/c ratio, the historical contribution factor, and the random factor. A standard version of the heuristic

search strategy has been defined for comparison with other alternative versions. The major parameters of the standard version include:

- TABU list length: 7,
- Markov Chain Length Increasing Rate: 20%,
- Initial Length of Markov Chain: 20,
- Control Parameter Decreasing Rate: 20%,
- Weight of Link V/C ratio: 1000.0
- Weight of Historical Contribution Factor:  $1.0e-4$ ,
- Weight of Random Factor: 10.0

Other assumptions include:

- Maximum number of iterations of the SA-TABU search: 500,
- Maximum number of iterations of the Frank-Wolfe algorithm: 500,
- Maximum number of No-Change before program terminates: 50,
- Conversion criteria in the Frank-Wolfe algorithm: 0.0001,
- Number of major iterations in the non-linear programming procedure: 50,
- Number of minor iterations in the non-linear programming procedure: 2000,
- Accuracy of constraints in the signal setting procedure: 0.0001

A summary of the results subjected to the standard heuristic search for the four test networks is presented in Table 6.1.



**Table 6.1** Summary of Numerical Experiments on Test Networks

|                 |                                     | Network<br>1 | Network<br>2 | Network<br>3 | Network<br>4 |
|-----------------|-------------------------------------|--------------|--------------|--------------|--------------|
|                 | No. Of Original Links               | 32           | 62           | 38           | 76           |
|                 | No. Of Expanded Links               | 96           | 180          | 124          | 272          |
| Network         | No. Of Internal Nodes               | 13           | 19           | 20           | 31           |
| Characteristics | No. Of Expanded Nodes               | 56           | 94           | 76           | 152          |
|                 | No. Of O-D Pairs                    | 12           | 42           | 182          | 240          |
|                 | Initial Ntwk. Tral. Time(Veh-hours) | 160.00       | 370.30       | 436.91       | 708.71       |
| Network         | Final Solution (Veh-hours)          | 146.10       | 326.35       | 393.56       | 686.80       |
| Performance     | % Improvement                       | 8.7%         | 11.9%        | 9.9%         | 3.1%         |
|                 | Iteration Best Solution First Found | 423          | 18           | 264          | 325          |
|                 | No. Of Iterations                   | 500          | 500          | 500          | 500          |

The efficiency of the heuristic search strategy is measured by the reduction of the objective function values of the UTNDP or network UE total travel time, which include both the cruising time between intersections and the delay time caused by intersection signals. The reduction of network UE total travel time ranges from 3.1% for network 4 to 11.9% for network 2.

As described in the previous chapters, the UTNDP is a bi-level non-linear NP-hard problem. The amount of computational time of solving the UTNDP increases rapidly with the increase in network size. The program was executed on a PC with Pentium II 350 processor and 64MB memory. A summary of the average computational times (clock time) for the four test networks is presented in Table 6.2.

**Table 6.2** Computational Time of Test Networks

| Network | Number of<br>Links | Number of Decision Variables |                             | No. of Constraints<br>in Signal Setting<br>NLP | Avg. Running<br>Time (minutes) |
|---------|--------------------|------------------------------|-----------------------------|--|--------------------------------|
|         |                    | (0,1)<br>Variables           | Signal Setting<br>Variables |  |                                |
| 1       | 96                 | 36                           | 25                          | 20   | 63                             |
| 2       | 180                | 58                           | 40                          | 29   | 343                            |
| 3       | 124                | 10                           | 30                          | 17   | 41                             |
| 4       | 272                | 104                          | 75                          | 48   | 512                            |

The computational time increases 7.11 times from network 1 to network 4, while the number of links of the networks only increases 1.83 times. The computational time of these test networks is dictated by the number of decision variables in the corresponding UTNDP, which include the (0,1) integer variables and continuous signal setting variables. The (0,1) integer variables are the network configuration decision variables, including the left turn control and land designation variables. The continuous signal setting variables include green splits of the intersections in the network and the offsets between each pair of adjacent intersections in the network. Although network 3 has more links than network 1, the computational time of network 3 is less than that of network 1 because the number of (0,1) variables in network 3 is less than one third of network 1.

## **6.2 Sensitivity Analysis on Major Algorithmic Parameters**

The primary objective of sensitivity analysis is to investigate the impact of some key parameters on the performance of the SA-TABU search procedure. For the simulated annealing process, sensitivity is tested on the control parameter (temperature) decreasing rate and the Markov chain length. A smaller control parameter decreasing rate and a longer Markov chain length can lead to a more smoothing annealing process that yields a good quality solution. However, it also requires a longer processing time. In order to find a desirable solution within a reasonable amount of computational time, a compromise needs to be made between the quality of the solution generated and the processing time. The results of the sensitivity analysis on the control parameters, the

dropping rate and the Markov chain length can be used as guidance in making such a compromise.

The TABU search procedure is used in the heuristic search to reduce the occurrence of cycling and to avoid local optimal. The most recently made moves are prevented from being updated again for certain number of iterations by placing them into a TABU list. The length of the TABU list reflects the number of iterations a recently updated variable needs to stay in the TABU list. The shorter the TABU list is, the larger the possibility that the search will focus on a historically ‘good’ search region, with an increased risk of the occurrence of cycles. The longer the TABU is, the larger the possibility that the search is directed to a new search region, and therefore the less opportunity the search is restrained to a local optimal, decreasing the risk of cycling.

The HEF places a value for each variable  $y$ , either abstract or real link of the network, which identifies the move to be made at every iteration from one solution state (network configuration) to the next. The HEF is composed of the current link  $v/c$  ratio, historical link contribution factor, and a random factor generated by a random number generator. The three elements are combined together linearly using weight coefficients for each element. The current link  $v/c$  ratio reflects the current traffic performance on the subject link, and the historical link contribution factor accumulates the impact of each update of the subject link on network-wide total travel time. The weight coefficients of these three elements dictate which links are selected for updating at each iteration, and thus have significant impact on the search procedure and the search results. The sensitivity analysis on these weights provides a better understanding on how the three HEF components affect the outcomes of the SA-TABU search procedure.

The sensitivity analysis was based on three different alternatives for the three parameters. The main characteristics of these versions are summarized in Tables 6.3 to 6.5 for sensitivity analysis on the TABU list length, heuristic search control parameters, and the HEF weight coefficients, respectively.

**Table 6.3** Sensitivity Test Versions on TABU List Length

| Alternative Version | TABU Length |
|---------------------|-------------|
| 1                   | 7           |
| 2                   | 11          |
| 3                   | 15          |

**Table 6.4** Sensitivity Test Versions on Heuristic Search Control Parameters

| Alternative Version | Markov Chain Length<br>Increasing Rate | Control Parameter<br>Decreasing Rate |
|---------------------|--|--------------------------------------|
| 1                   | 20%                                    | 20%                                  |
| 2                   | 30%                                    | 10%                                  |
| 3                   | 10%                                    | 30%                                  |

**Table 6.5** Sensitivity Test Versions on HEF Weight Coefficients

| Alternative Version | v/c Ratio<br>Multiplier | Historical Contribution<br>Factor Multiplier | Random Factor<br>Multiplier |
|---------------------|-------------------------|--|-----------------------------|
| 1                   | 1000                    | 1.0e-4                                       | 10                          |
| 2                   | 500                     | 2.0e-4                                       | 5                           |
| 3                   | 2000                    | 0.5e-4                                       | 20                          |

Among the four test networks, only the first three are used for sensitivity analysis purposes. The results of the sensitivity tests for the three test networks are discussed in the following sections.

### 6.2.1 Sensitivity Tests on TABU List Length

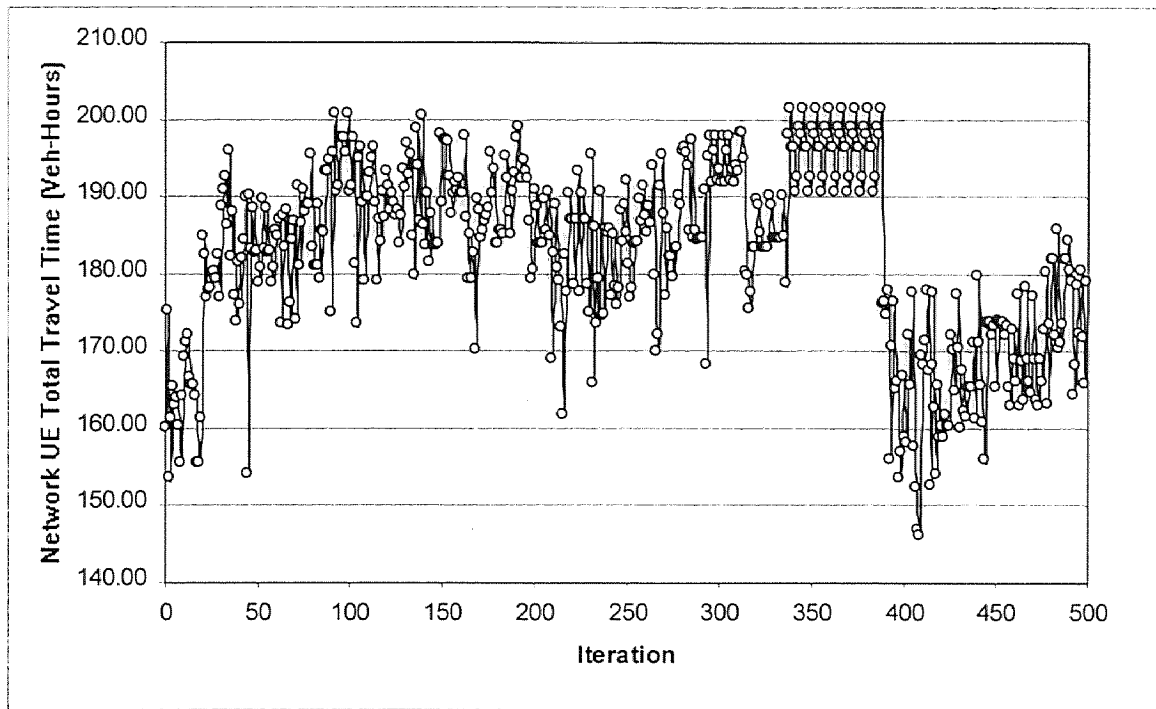
The appropriate TABU list length depends primarily on the size and structure of the test network. Glover (27) recommended using a length of 7, and this length is set as the standard version in this study. Since the number of links in the three test networks are fairly large after network expansion, the TABU list length needs to be set in a way that most feasible solution regions are explored, while at the same time the search is detailed enough in the local solution regions so that the search won't easily jump out of the local region before a good local optimal is located. If the TABU list length is short, the 'good' solution regions will appear repetitively during the search procedure, and other regions are less likely to be explored. If the TABU list length is long, the explored trial region is larger, however the 'good' solution regions are not as well explored as in the case of short TABU list length. Because of the relatively large number of links on the expanded networks, two alternative versions were explored with longer TABU list lengths, 11 and 15 respectively. The summaries of the sensitivity tests on the TABU list length are presented in Table 6.6. The trial state and the current state performances of the TABU list length of alternative version 1 of each test networks are presented in Figures 6.1 to 6.6. The following observations are made from Table 6.6.

- The mean of the trial solution states is always larger than that of the current solution state, which reflects the selective nature of the SA-TABU search procedure. Only trial solution states that meet the stochastic selection criteria in the simulated annealing step in the SA-TABU procedure are accepted as current solution states.

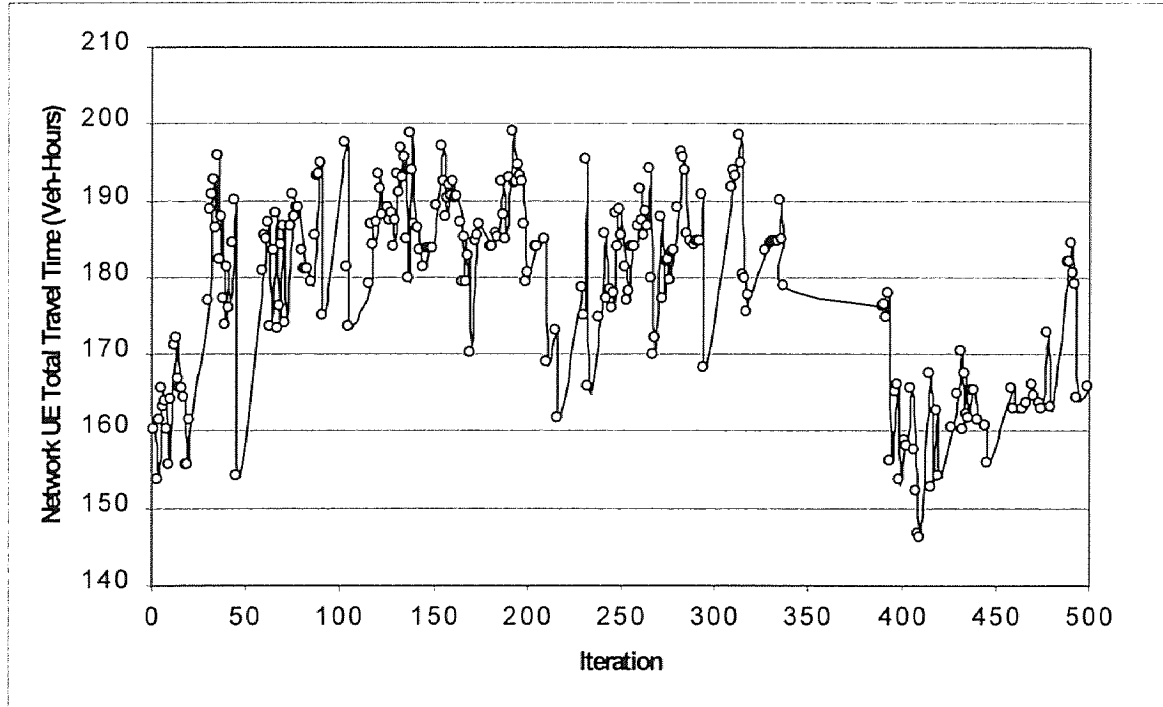
- For all the three test networks, the means of total network travel time of both the current solution state and the trial solution state decrease as the TABU list length increases from 7 to 11, and then to 15. This may be because of the inappropriateness of applying long TABU list length when the number of updateable variables is not large enough, as it forces the search to a worse quality region when a significant number of updateable links is put into the TABU list.
- Alternative version 1 produces the best results for all the three test networks. A TABU list length of 7 is suggested for networks with limited updateable links, as ‘good’ solution regions need to be explored as much as possible before the search is directed to another region. However, it is noted that more research should be conducted on larger networks to find the most ‘optimal’ TABU list lengths.

### 6.2.2 Sensitivity Tests on Markov Chain Length and Control Parameter

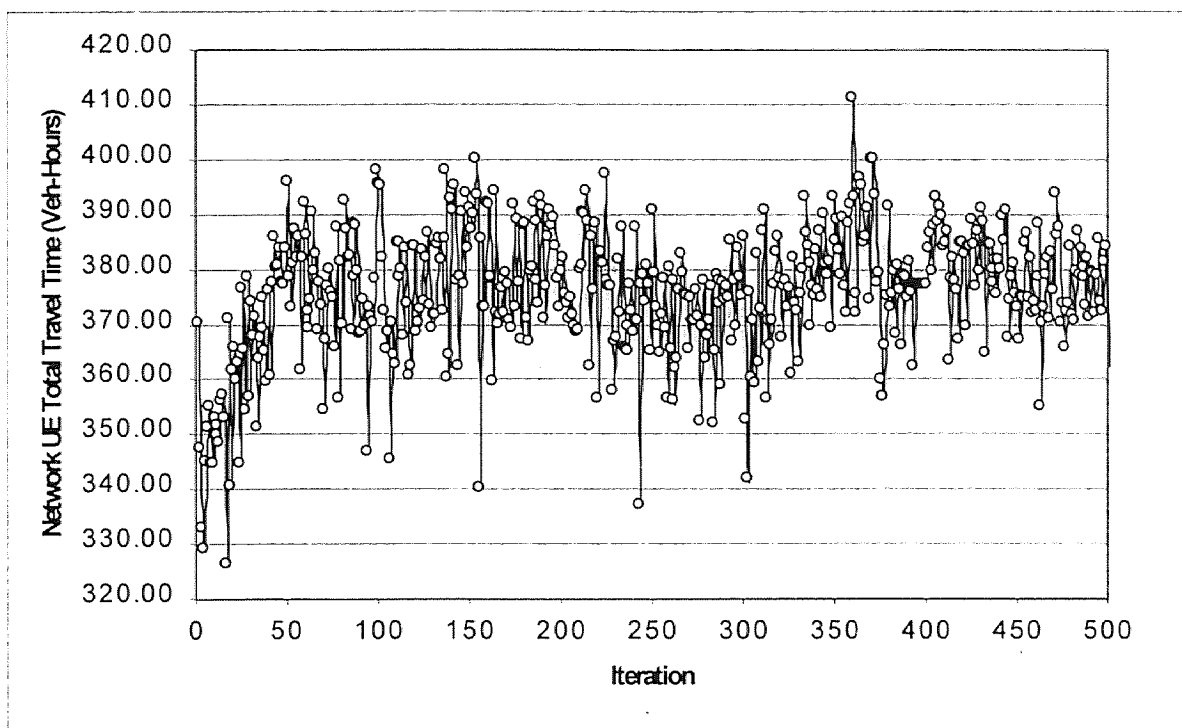
The Markov chain length and the control parameter dictate the pattern of the simulated annealing process. Besides the current solution state and the new solution state objective functions, the temperature is the only factor in the acceptance criteria (see equation 3.29). The temperature dictates the pace of the simulated annealing procedure. The larger the temperature is, the easier the acceptance criteria are met. At the beginning of the search, the temperature is usually set to a large value, and therefore most of the moves are accepted. As the temperature is decreased at a fixed rate as the number of iterations increases, only a few good solution states will be accepted. The larger the temperature decreasing rate is, the more restrictive the SA-TABU search procedure is.



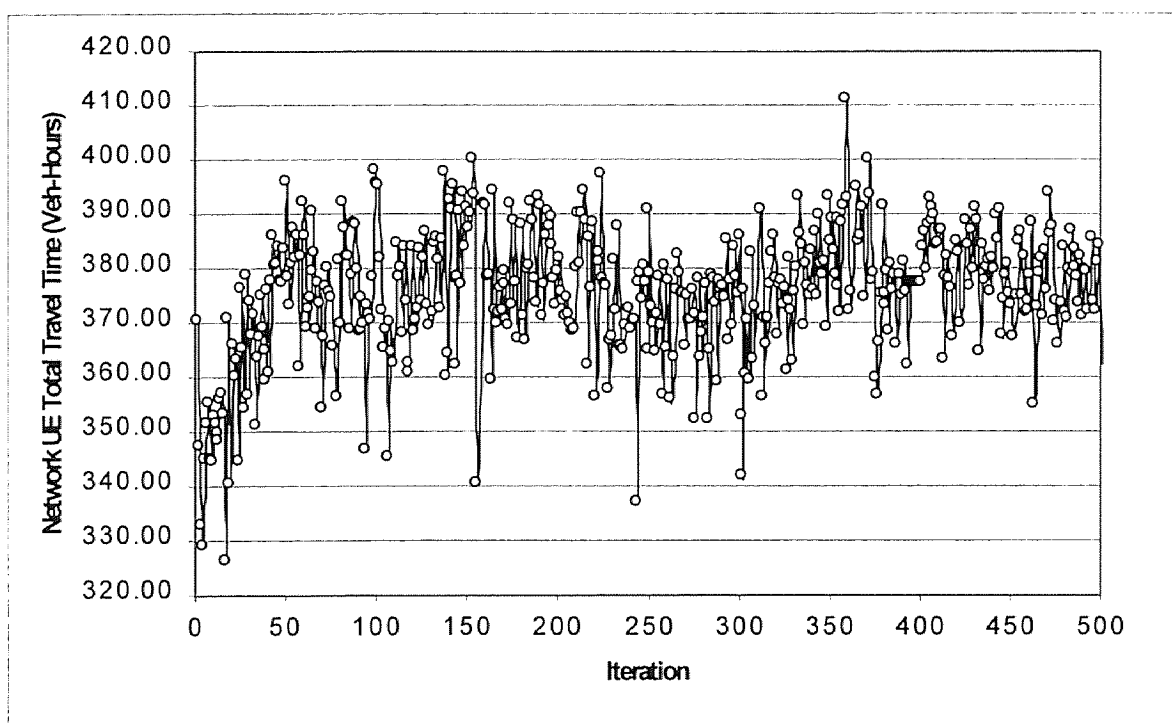
**Figure 6.1** Network UE Total Travel Time (Veh.-hours) VS. Iteration Number; (Network 1, Alternative Version 1, Trial Solution State)



**Figure 6.2** Network UE Total Travel Time (Veh.-hours) VS. Iteration Number; (Network 1, Alternative Version 1, Current Solution State)

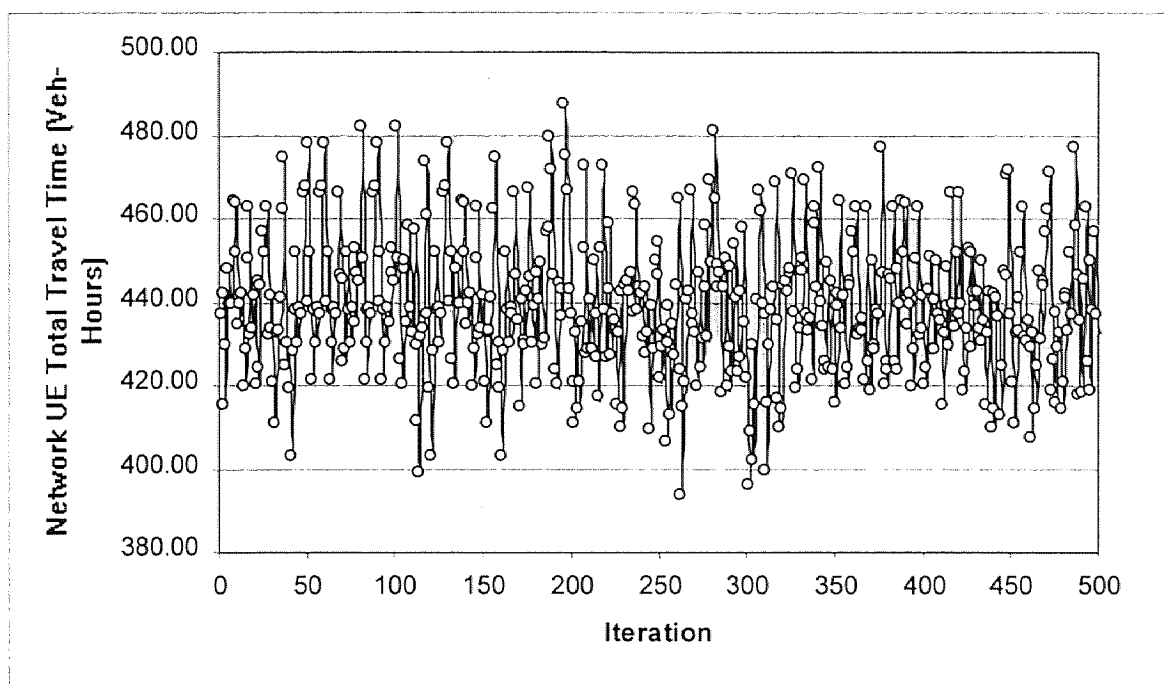


**Figure 6.3** Network UE Total Travel Time (Veh.-hours) VS. Iteration Number; (Network 2, Alternative Version 1, Trial Solution State)

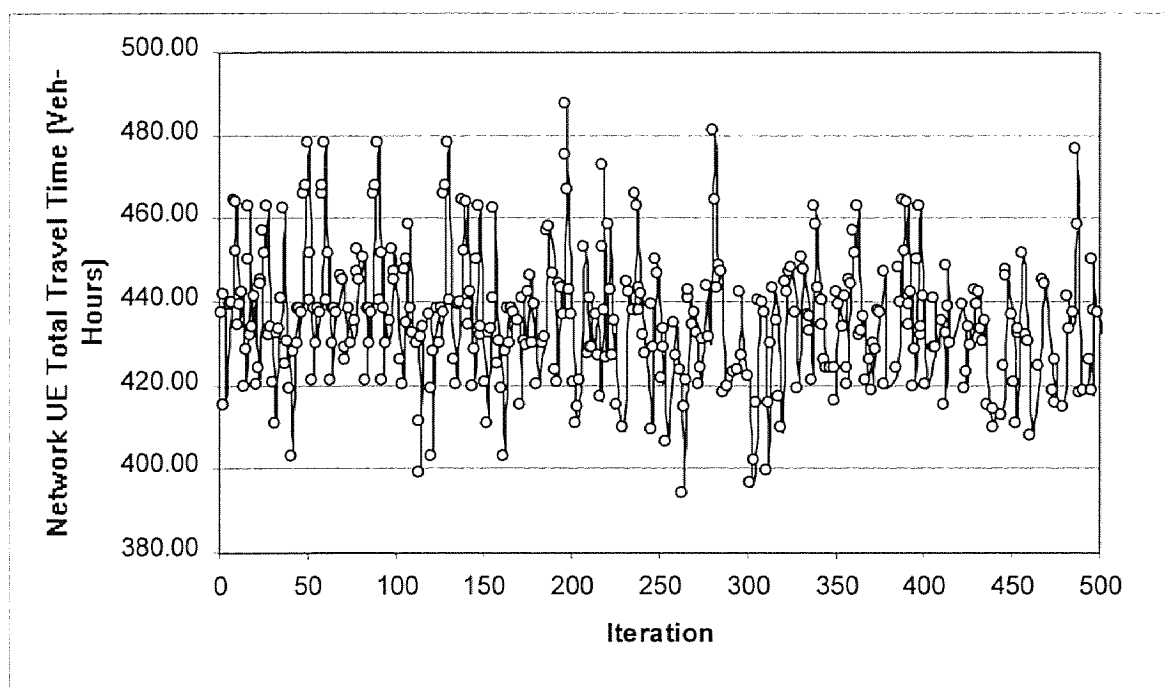


**Figure 6.4** Network UE Total Travel Time (Veh.-hours) VS. Iteration Number; (Network 2, Alternative Version 1, Current Solution State)





**Figure 6.5** Network UE Total Travel Time (Veh.-hours) VS. Iteration Number; (Network 3, Alternative Version 1, Trial Solution State)



**Figure 6.6** Network UE Total Travel Time (Veh.-hours) VS. Iteration Number; (Network 3, Alternative Version 1, Current Solution State)

The transformation from the current solution state to the subsequent solution state is called a transition in the simulated annealing procedure. A transition consists of both the application of acceptance criteria and the application of the generation mechanism, which is used to generate a new solution state. Usually a number of transitions is generated under a fixed temperature, and the number of transitions is determined by Markov chain length. A large Markov chain length increasing rate and/or small temperature dropping rate lead to a less restrictive search procedure that trial states are more easily to be accepted. Consequently, the search region is widened and the search quality is improved. However, this also leads to a slower progressing speed, and it creates a significant disadvantage on the efficiency of the algorithm. On the other hand, a small Markov chain length increasing rate and/or large temperature dropping rate lead to a faster search procedure, but it also narrows down the search region and increases the risk of ending the search procedure at an undesirable local optimal. Compared with the alternative version 1, alternative version 2 represents a less restrictive and slower search procedure, while alternative version 3 represents a more restrictive and faster search procedure. The results of the sensitivity tests on Markov chain length and temperature are summarized in Table 6.7. The following observations are noted from Table 6.7.

- The mean of the network total travel time of the trial solution states is always larger than that of the current solution state, which reflects the selective nature of the SA-TABU search procedure.
- For all the three test networks, the mean of both the current state and the trial state decreases from alternative version 2 to alternative version 1 and to alternative version

3, which reflects the fact that a large Markov increasing rate and /or small temperature dropping rate are less restrictive in moving from one iteration to the next.

- Alternative version 3 produces the best results of all the three test networks. For all the three networks, the feasible solution spaces are relatively large after network expansion, and a faster and less restrictive global search such as alternative version 3 help to locate a better solution state rather than a slower narrow local search such as alternative version 2.

### **6.2.3 Sensitivity Tests on the Heuristic Evaluation Function (HEF) Coefficients**

The HEF has three components, the current v/c ratio, the historical contribution factor, and the random factor. The selection of move to be made and link(s) to enter/exit the current solution state, is significantly dependent on the weight of these three components. If a larger weight is given to current link v/c ratios, the links with large v/c ratios are more likely to be selected for updating so that the traffic performance can be improved. If a larger weight is given to the historical contribution factor, then more emphasis is given to the historical factor, and links that historically performed well are more likely to be included in the final solutions. The random factor is included in the HEF so that the search process is more stochastic, and the search explores a wider region, aiding to the diversification of the search and jumping out of local optima. Compared with the alternative version 1, alternative version 2 put more emphasis on the historical factor, increasing the risk that some 'good' regions are expected to appear repetitively in the search procedure. Alternative version 3 put more emphasis on the current link v/c ratio, and the exploration of the solution regions is less restrictive. The results of sensitivity

tests on HEF coefficients are summarized in Table 6.8. The following observations were made from Table 6.8.

- The mean of the network travel time of the trial solution state is always larger than that of the current solution state, which reflects the selective nature of the SA-TABU search procedure.
- For all the three test networks, alternative version 2 has the smallest mean of both the current state and trial state, which indicates that a larger historical contribution weight and a smaller current v/c ratio weight lead to better quality search regions. This implies that solution states that performed well in previous iterations should be explored more explicitly, and more emphasis should be given to the historical contribution factor.
- Alternative version 2 produces the best results of all the three test networks. A large historical contribution factor weight and/or small current v/c ratio weight are recommended for this SA-TABU heuristic. For these small sized networks, the change of network configuration variables (left turn control variables and lane designation variables) can easily produce a significant change in link v/c ratios because of the re-distribution of traffic flows.

**Table 6.6** Summary of Sensitivity Analysis on TABU List Length

| Network | Alternative Version | TABU List Length | Best Solution | Iterations | Mean of Curt . Sol. State | Std. Dev. of Curt. Sol. State | Mean of Tril. Sol. State | Std. Dev. of Tril. Sol. State |
|---------|---------------------|------------------|---------------|------------|---------------------------|-------------------------------|--------------------------|-------------------------------|
| 1       | 1                   | 7                | 525965.1      | 423        | 645442                    | 42533.95                      | 657211.6                 | 41997.99                      |
|         | 2                   | 11               | 542595.6      | 321        | 644451.6                  | 40432.6                       | 648595.3                 | 39056.95                      |
|         | 3                   | 15               | 551552.5      | 32         | 628411.2                  | 35019.48                      | 642426.6                 | 38611.45                      |
| 2       | 1                   | 7                | 1174892       | 18         | 1351610                   | 42323.42                      | 1352800                  | 42134.04                      |
|         | 2                   | 11               | 1184891       | 5          | 1381236                   | 61496                         | 1384620                  | 61363.12                      |
|         | 3                   | 15               | 1184891       | 5          | 1362571                   | 50893.86                      | 1366642                  | 50961.63                      |
| 3       | 1                   | 5                | 1416825       | 264        | 1569203                   | 56541.28                      | 1579979                  | 59609.26                      |
|         | 2                   | 7                | 1432352       | 393        | 1570481                   | 63772.4                       | 1576196                  | 62552.47                      |
|         | 3                   | 9                | 1422733       | 432        | 1561972                   | 57868.85                      | 1570067                  | 60186.52                      |

**Table 6.7** Summary of Sensitivity Analysis on Markov Chain Length and Control Parameter (Temperature)

| Network | Alternative Version | Markov Chain Incr. Rate | Ctrl. Parm. Decr. Rate | Best Solution   | Iterations | Mean of Curt . Sol. State | Std. Dev. of Curt. Sol. State | Mean of Tril. Sol. State | Std. Dev. of Tril. Sol. State |
|---------|---------------------|-------------------------|------------------------|-----------------|------------|---------------------------|-------------------------------|--------------------------|-------------------------------|
| 1       | 1                   | 20%                     | 20%                    | 525965.1        | 423        | 645442                    | 42533.95                      | 657211.6                 | 41997.99                      |
|         | 2                   | 30%                     | 10%                    | 552796          | 4          | 664088.1                  | 34174.47                      | 668825.6                 | 32637.84                      |
|         | 3                   | 10%                     | 30%                    | <b>505253.1</b> | <b>273</b> | <b>598240.1</b>           | <b>42868.58</b>               | <b>621770.4</b>          | <b>41214.16</b>               |
| 2       | 1                   | 20%                     | 20%                    | 1174892         | 18         | 1351610                   | 42323.42                      | 1352800                  | 42134.04                      |
|         | 2                   | 30%                     | 10%                    | 1174892         | 18         | 1355377                   | 43165.33                      | 1357732                  | 43463.6                       |
|         | 3                   | 10%                     | 30%                    | <b>1145235</b>  | <b>443</b> | <b>1340444</b>            | <b>50563.87</b>               | <b>1347850</b>           | <b>49121.65</b>               |
| 3       | 1                   | 20%                     | 20%                    | 1416825         | 264        | 1569203                   | 56541.28                      | 1579979                  | 59609.26                      |
|         | 2                   | 30%                     | 10%                    | 1416825         | 398        | 1583844                   | 58838.67                      | 1588553                  | 59958.21                      |
|         | 3                   | 10%                     | 30%                    | <b>1405365</b>  | <b>325</b> | <b>1555450</b>            | <b>58930.76</b>               | <b>1567207</b>           | <b>55757.38</b>               |

**Table 6.8** Summary of Sensitivity Analysis on HEF Coefficients

| Network | Alternative Version | v/c Mult. | Histr. Con. Mult. | Rand. Mult. | Best Solution | Iterations | Mean of Curt . Sol. State | Std. Dev. of Curt. Sol. State | Mean of Tril. Sol. State | Std. Dev. of Tril. Sol. State |
|---------|---------------------|-----------|-------------------|-------------|---------------|------------|---------------------------|-------------------------------|--------------------------|-------------------------------|
| 1       | 1                   | 1000      | 0.00010           | 10          | 525965.1      | 321        | 645442                    | 42533.95                      | 657211.6                 | 41997.99                      |
|         | 2                   | 500       | 0.00020           | 10          | 499684.1      | 406        | 624180.6                  | 41748.82                      | 638883.5                 | 43995.95                      |
|         | 3                   | 2000      | 0.00005           | 10          | 526930.8      | 30         | 629086.2                  | 33539.36                      | 645350                   | 34520.7                       |
| 2       | 1                   | 1000      | 0.00010           | 10          | 1174892       | 18         | 1351610                   | 42323.42                      | 1352800                  | 42134.04                      |
|         | 2                   | 500       | 0.00020           | 10          | 1174892       | 18         | 1332085                   | 39373.94                      | 1333341                  | 38981.82                      |
|         | 3                   | 2000      | 0.00005           | 10          | 1197412       | 48         | 1375388                   | 49887.34                      | 1377117                  | 49798.02                      |
| 3       | 1                   | 1000      | 0.00010           | 10          | 1427125       | 178        | 1570283                   | 58844.07                      | 1581008                  | 58937.82                      |
|         | 2                   | 500       | 0.00020           | 10          | 1416825       | 264        | 1569203                   | 56541.28                      | 1579979                  | 59609.26                      |
|         | 3                   | 2000      | 0.00005           | 10          | 1466439       | 444        | 1574142                   | 54908.13                      | 1583655                  | 57168.85                      |

## CHAPTER 7

### CONCLUSIONS AND FUTURE RESEARCH

#### 7.1 Summary of the UTNDP

The motivation for this study stems from the need of alleviating traffic congestion in urban transportation networks by implementing appropriate traffic control strategies. These control strategies addressed in this UTNDP include signal setting control, intersection left turn movement control and lane designation control. Appropriate intersection left turn movement control can reduce conflicts caused by turning vehicles. Re-designation of lanes can better accommodate peak direction traffic. An integrated signal setting subroutine in the UTNDP can allocate signal resources more reasonably in response to link flows and network configurations. The analogy between the network design problem and the optimization of traffic control strategies motivates the formulation of the UTNDP model to optimize traffic control strategies. The UTNDP model is a bi-level nonlinear mixed integer programming model with the minimization of network wide total travel time as its objective. On the upper level, the traffic control strategies, intersection left turn control, lane designation and signal setting control are optimized with fixed flows, while on the lower level, an asymmetric assignment is conducted based on the current network configurations. Intersection left turn control and lane designation variables are discrete variables, while signal setting and link flows are continuous variables. A realistic link delay estimation procedure, which follows the 1997 HCM (46) procedure, is used in the UTNDP model. Link delays not only depend on link flows, but also depend on signal settings, network configurations, and traffic control



policies. The presence of link interactions leads to the asymmetric nature of the traffic assignment step in the lower level of the UTNDP model, and it requires a diagonalization procedure that takes into account the impact of conflicting link flows on the delay on the subject link. A streamlined diagonalization procedure is used in solving the asymmetric traffic assignment. The UTNDP is a NP-Hard problem, and the complexity of the UTNDP makes it impossible to find the optimal solution. An iterative heuristic search procedure is developed to solve the UTNDP model. The heuristic search procedure developed in this study is SA-TABU procedure that combines the main characteristics of the simulated annealing and TABU search procedures. The heuristic search is guided by a heuristic evaluation function (HEF), which has three components, the current link  $v/c$  ratio, the historical contribution factor and the random factor. To test the efficiency of the solution procedure, four test networks are designed and used as the basis for the numerical tests.

The major contributions of this dissertation includes:

- The formulation of a comprehensive Urban Transportation Network Design Problem (UTNDP), which requires optimizations at the network structural level, signal setting level and the traffic assignment level, is first of its kind. The UTNDP is formulated as a bi-level nonlinear mixed integer programming problem, which can be used to select the appropriate signal and traffic control strategies systematically. The interactive nature between the signal and network configuration optimization and the traffic assignment requires a model to integrate these two aspects together rather than solve them separately. The design of the UTNDP model reflects the integration of these two aspects.

- Development of an asymmetric traffic assignment procedure to find link flows. The existence of large amounts of intersection turnings in a urban transportation network requires an asymmetric traffic assignment procedure to reflect the interaction of the conflicting link flows. The diagonalization used in the traffic assignment procedure is designed to account for the impact of conflicting opposite through traffic flows on the delay of the subject left turn movement. This contribution is an extension of Berka et al.'s (13) work, which first addressed this problem.
- Development of a realistic link delay estimation procedure which takes into account link flows, signal settings, and network configurations. The complex nature of the factors affecting link delays in an urban transportation network makes it inappropriate to use BPR type curves as the link performance functions. A realistic link performance function is designed to include signal settings and link flows as dependant variables.
- Development of a heuristic search strategy to solve the UTNDP. The SA-TABU search procedure is used to solve the UTNDP, which combines the major characteristics of the TABU search and the Simulated Annealing search procedures. The UTNDP results were obtained in reasonable amounts of time for all the 4 test networks. To test the efficiency of the model and the solution procedure, numerical tests need to be conducted on various sizes of test networks.
- Development of a signal setting optimization procedure that is integrated as part of the UTNDP. As an essential part of the UTNDP, signal setting is critical to both the optimizations of other traffic control strategies and the traffic assignments in the

network. Signal setting not only included green splits and cycle length as its decision variables, but also included offsets as decision variables as well.

## 7.2 Conclusions

The following conclusions are made from this research:

- The efficiency of urban transportation networks can be improved by implementing appropriate traffic control strategies, such as intersection left turn control, lane designation control, and signal timing control, without physical expansion of urban streets. The network UE total travel time of the four test networks in this study were reduced by 8.7%, 11.9%, 9.9% and 3.1% for networks 1, 2, 3 and 4, respectively. By implementing intersection left turn control, conflicting flows are eliminated and thus reduce network-wide total travel time. Redesignation of number of lanes can better accommodate traffic in peak directions and thus alleviate peak direction congestion.
- The introduction of a signal setting step in the UTNDP makes the model more realistic, because the link flow and control strategy dependent signal setting scheme can better reflect the signal requirement of traffic flows. The inclusion of offsets as the signal setting variables can better reflect the coordinated nature of the signalized urban transportation networks, although it also increases the complexity of the model and the solution search procedure. On three major arterials in network 4, the bandwidths, which are widely used by engineers as indices of signal coordination, were improved after the signal and traffic control strategies were optimized.
- The realistic link delay functions used in this study, rather than the BPR type curves, take into account the impact of signal setting and traffic control strategies on link

delays. This is consistent with the fact that large portion of delays occurred at intersections rather than on traveling between intersections on urban networks.

Numerical test results have shown that, as the O-D demand increases, the turning movement delays, especially the left turn movement delays, increase significantly.

This demonstrated that the use of realistic delay functions in transportation modeling is extremely important when the traffic flow is heavy in the subject transportation network, such as an urban transportation network.

- The asymmetric traffic assignment, which is solved by using the streamlined diagonalization algorithm, can better represent the impact of conflicting flows on the delay of the subject link. The conflicting pair of links on an urban network includes the through movement and the left movement on the opposite direction, or vice versa. Because of the unprotected left turn phases at most intersections in an urban network, the impact of conflicting flow on delay of the subject link can not be omitted. Numerical tests have shown that delays occurring on intersection left turn links occupy a large portion of the total delays on the network, which is especially true when the traffic flow on the subject network is heavy.
- The cruise times between two adjacent intersections are not as sensitive to link volumes as intersection turning movement delays to link volumes. The numerical test on network 4 has shown that with a 50% decrease in O-D demands, the average link cruise time decreased only 3.3%, while the average left turn movement delays decreased 52.1%.
- The implementation of appropriate signal, intersection turning, and lane designation controls can improve traffic performances. For test network 4, the network-wide

average speed was improved from 15.0 mph to 15.3 mph, while the average travel time of an O-D pair was reduced from 3 minutes 5 seconds to 3 minutes 1 seconds. The number of over congested links with v/c ratios greater than 1.0 was reduced from 4 to 3.

- The SA-TABU heuristic search procedure is an efficient search procedure in finding near optimal solutions for the UTNDP. It combines the aggressive TABU search characteristic with the conservative simulated annealing characteristic so that a reasonable compromise is made between directing the search to a new solution region and concentrating on the current search region. For the four test networks, acceptable results were obtained in a reasonable period of time.
- The three major components of the SA-TABU strategy are simulated annealing, TABU search and the heuristic evaluation function (HEF). For the simulated annealing process, a smaller control parameter decreasing rate and a longer Markov chain length can lead to a more smoothing annealing process that yields a good quality solution. However, it also requires a longer processing time. For the TABU search procedure, the shorter the TABU list is, the larger the possibility that the search will focus on a historically 'good' search region, with an increased risk of cycling. The longer the TABU is, the larger the possibility that the search is directed to a new search region, and therefore the less opportunity the search is restrained to a local optimal, decreasing the risk of cycling. The weight coefficients of these three elements dictate which links are selected for updating at each iteration, and thus have significant impact on the search procedure and the search results.

- The amount of computational time of solving the UTNDP increases rapidly with the increase in network size. The computational time increases 7.11 times from network 1 to network 4, while the number of links of the networks only increases 1.83 times.

### 7.3 Future Research

- The two major traffic control strategies studied in this research are the intersection left turn movement control and the lane designation. However, another important control strategy needs to be addressed in future research is the selection of roads which should implement one-way traffic control policies as opposed to two-way traffic policies. The availability of paths between any O-D pairs needs to be carefully addressed if a one-way traffic policy is also considered.
- At the traffic assignment level, the 1994 HCM delay estimation model is used as the link performance function, which include link flows and green splits, and cycle length as its independent variables. The HCM model can not replace Gartner's model in the signal setting level because offsets are not considered as independent variable in the HCM formulation. On the other hand, Gartner's model can not replace the HCM formulation because it can not be converted to movement based delay estimations, which is essential in our application. This discrepancy needs to be resolved in the future, and a consistent movement based delay estimation model needs to be developed to include link flows, green splits, cycle length and offsets as the independent variables.
- Because of the link capacity constraints in the signal setting step, only under-congested conditions are addressed in this study. The formulation of the UTNDP

model under congested conditions needs to be studied in the future which requires a modified signal setting model that can take into account congested traffic conditions.

- Eventually, the static UE traffic assignment used in this study should be replaced by a more accurate dynamic traffic assignment that would better capture the user travel behavior under dynamic changing conditions.
- The inclusion of offsets in the signal setting model introduces integer variables in the loop constraints of a nonlinear programming model, and it increases the complexity of the model significantly. In this study, only a limited number of major loop constraints is included in the signal setting step for each test network. A more accurate procedure needs to be developed to address the loop constraint issue.
- Other heuristic search procedures are recommended to explore the performance of the search procedure, in particular, the techniques of neural network and genetic algorithms. Extensive tests need to be conducted on larger networks to test the efficiency of the search procedure.
- In future research, objectives other than network-wide total travel time could be included in the objective function, such as fuel consumption, environmental impacts, and multiple classes of users such as autos, trucks, buses etc.
- Since the computational demand of the UTNDP model is extensive, parallel-computing techniques may need to be explored to increase the computational speed

## **APPENDIX A**

### **SUMMARY OF UTNDP RESULTS OF TEST NETWORK 4**



**Table A Summary of UTNDP Results**

| Node     |        | Average Flow<br>(veh./hour) |       | Average Delay<br>(sec./veh.) |       | Left Turn |           | No. of Lanes |       | V/C ratio |       |
|----------|--------|-----------------------------|-------|------------------------------|-------|-----------|-----------|--------------|-------|-----------|-------|
| Starting | Ending | Original                    | Final | Original                     | Final | Original  | Final     | Original     | Final | Original  | Final |
| 33       | 38     | 148                         | 287   | 26.6                         | 33.6  | Permitted | Permitted | n/a          | n/a   | n/a       | n/a   |
| 33       | 36     | 572                         | 433   | 15                           | 14.3  | n/a       | n/a       | n/a          | n/a   | n/a       | n/a   |
| 33       | 34     | 60                          | 60    | 15                           | 14.3  | n/a       | n/a       | n/a          | n/a   | n/a       | n/a   |
| 35       | 40     | 45                          | 45    | 15.4                         | 26.5  | Permitted | Permitted | n/a          | n/a   | n/a       | n/a   |
| 35       | 38     | 354                         | 315   | 15.9                         | 11.5  | n/a       | n/a       | n/a          | n/a   | n/a       | n/a   |
| 35       | 36     | 381                         | 420   | 15.9                         | 11.5  | n/a       | n/a       | n/a          | n/a   | n/a       | n/a   |
| 36       | 41     | 1419                        | 1154  | 47.1                         | 46.2  | n/a       | n/a       | 2            | 2     | 1.09      | 0.85  |
| 37       | 34     | 277                         | 315   | 38                           | 28.5  | Permitted | Permitted | n/a          | n/a   | n/a       | n/a   |
| 37       | 40     | 510                         | 510   | 10.4                         | 15.6  | n/a       | n/a       | n/a          | n/a   | n/a       | n/a   |
| 37       | 38     | 198                         | 45    | 10.4                         | 15.6  | n/a       | n/a       | n/a          | n/a   | n/a       | n/a   |
| 38       | 75     | 701                         | 647   | 15                           | 14.9  | n/a       | n/a       | 2            | 2     | 0.72      | 0.51  |
| 39       | 36     | 466                         | 301   | 33.6                         | 33.9  | Permitted | Permitted | n/a          | n/a   | n/a       | n/a   |
| 39       | 34     | 488                         | 450   | 24.7                         | 13.4  | n/a       | n/a       | n/a          | n/a   | n/a       | n/a   |
| 39       | 40     | 270                         | 270   | 24.7                         | 13.4  | n/a       | n/a       | n/a          | n/a   | n/a       | n/a   |
| 41       | 46     | 105                         | 133   | 40.1                         | 27    | Permitted | Permitted | n/a          | n/a   | n/a       | n/a   |
| 41       | 44     | 1209                        | 916   | 10                           | 7.4   | n/a       | n/a       | n/a          | n/a   | n/a       | n/a   |
| 41       | 42     | 105                         | 105   | 10                           | 7.4   | n/a       | n/a       | n/a          | n/a   | n/a       | n/a   |
| 43       | 48     | 133                         | 90    | 32.7                         | 28.4  | Permitted | Permitted | n/a          | n/a   | n/a       | n/a   |
| 43       | 46     | 308                         | 360   | 15.3                         | 16.6  | n/a       | n/a       | n/a          | n/a   | n/a       | n/a   |
| 43       | 44     | 309                         | 300   | 15.3                         | 16.6  | n/a       | n/a       | n/a          | n/a   | n/a       | n/a   |
| 44       | 49     | 1630                        | 1335  | 31.8                         | 31.2  | n/a       | n/a       | 2            | 2     | 1.13      | 0.84  |
| 45       | 42     | 224                         | 225   | 72.4                         | 38.4  | Permitted | Permitted | n/a          | n/a   | n/a       | n/a   |
| 45       | 48     | 807                         | 690   | 29.6                         | 14.1  | n/a       | n/a       | n/a          | n/a   | n/a       | n/a   |
| 45       | 46     | 99                          | 45    | 29.6                         | 14.1  | n/a       | n/a       | n/a          | n/a   | n/a       | n/a   |
| 46       | 83     | 513                         | 538   | 14.8                         | 14.8  | n/a       | n/a       | 2            | 2     | 0.38      | 0.38  |
| 47       | 44     | 111                         | 120   | 23.9                         | 35.3  | Permitted | Permitted | n/a          | n/a   | n/a       | n/a   |
| 47       | 42     | 512                         | 510   | 9.7                          | 5.7   | n/a       | n/a       | n/a          | n/a   | n/a       | n/a   |

Table A (Continued)

|    |    |      |      |      |      |           |           |     |     |      |      |
|----|----|------|------|------|------|-----------|-----------|-----|-----|------|------|
| 47 | 48 | 46   | 90   | 9.7  | 5.7  | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 48 | 37 | 985  | 870  | 45.7 | 45.4 | n/a       | n/a       | 2   | 2   | 0.57 | 0.55 |
| 49 | 54 | 59   | 150  | 61.9 | 37.5 | Permitted | Permitted | n/a | n/a | n/a  | n/a  |
| 49 | 52 | 1380 | 1035 | 14.8 | 10.1 | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 49 | 50 | 190  | 150  | 14.8 | 10.1 | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 51 | 56 | 195  | 195  | 31.9 | 30.3 | Permitted | Permitted | n/a | n/a | n/a  | n/a  |
| 51 | 54 | 650  | 688  | 17.3 | 17.4 | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 51 | 52 | 325  | 287  | 17.3 | 17.4 | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 52 | 57 | 1857 | 1502 | 64.8 | 63.1 | n/a       | n/a       | 2   | 2   | 1.15 | 1.10 |
| 53 | 50 | 11   | 150  | 195  | 92.1 | Permitted | Permitted | n/a | n/a | n/a  | n/a  |
| 53 | 56 | 876  | 705  | 18   | 10   | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 53 | 54 | 270  | 263  | 18   | 10   | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 54 | 91 | 978  | 1101 | 15.2 | 15.4 | n/a       | n/a       | 2   | 2   | 0.74 | 0.73 |
| 55 | 52 | 151  | 180  | 45.5 | 44.3 | Permitted | Permitted | n/a | n/a | n/a  | n/a  |
| 55 | 50 | 609  | 510  | 12   | 10.2 | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 55 | 56 | 59   | 60   | 12   | 10.2 | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 56 | 45 | 1130 | 960  | 30.8 | 30.4 | n/a       | n/a       | 2   | 2   | 0.66 | 0.65 |
| 57 | 62 | 59   | 212  | 76.9 | 38.6 | Permitted | Permitted | n/a | n/a | n/a  | n/a  |
| 57 | 60 | 1544 | 1095 | 20.6 | 8.4  | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 57 | 58 | 254  | 196  | 20.6 | 8.4  | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 59 | 64 | 280  | 254  | 34.1 | 40.9 | Permitted | Permitted | n/a | n/a | n/a  | n/a  |
| 59 | 62 | 424  | 451  | 14.6 | 18.8 | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 59 | 60 | 121  | 120  | 14.6 | 18.8 | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 60 | 65 | 1859 | 1336 | 32.4 | 31.2 | n/a       | n/a       | 2   | 2   | 1.10 | 0.64 |
| 61 | 58 | 112  | 105  | 33.4 | 38.2 | Permitted | Permitted | n/a | n/a | n/a  | n/a  |
| 61 | 64 | 810  | 804  | 19.4 | 3.9  | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 61 | 62 | 60   | 60   | 19.4 | 3.9  | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 62 | 99 | 544  | 723  | 14.8 | 15   | n/a       | n/a       | 2   | 2   | 0.42 | 0.59 |
| 63 | 60 | 195  | 121  | 17.2 | 28.3 | Permitted | Permitted | n/a | n/a | n/a  | n/a  |
| 63 | 58 | 504  | 569  | 6.3  | 10.5 | n/a       | n/a       | n/a | n/a | n/a  | n/a  |

Table A (Continued)

|           |           |            |          |             |            |                  |                   |            |            |            |            |
|-----------|-----------|------------|----------|-------------|------------|------------------|-------------------|------------|------------|------------|------------|
| 63        | 64        | 66         | 60       | 6.3         | 10.5       | n/a              | n/a               | n/a        | n/a        | n/a        | n/a        |
| 64        | 53        | 1156       | 1118     | 61.6        | 61.5       | n/a              | n/a               | 2          | 2          | 0.86       | 0.74       |
| <b>65</b> | <b>70</b> | <b>420</b> | <b>0</b> | <b>49.2</b> | <b>n/a</b> | <b>Permitted</b> | <b>Prohibited</b> | <b>n/a</b> | <b>n/a</b> | <b>n/a</b> | <b>n/a</b> |
| 65        | 68        | 750        | 750      | 14.8        | 12.3       | n/a              | n/a               | n/a        | n/a        | n/a        | n/a        |
| 65        | 66        | 690        | 586      | 14.8        | 12.3       | n/a              | n/a               | n/a        | n/a        | n/a        | n/a        |
| 67        | 72        | 374        | 310      | 29.9        | 28.1       | Permitted        | Permitted         | n/a        | n/a        | n/a        | n/a        |
| 67        | 70        | 377        | 440      | 14.4        | 14.3       | n/a              | n/a               | n/a        | n/a        | n/a        | n/a        |
| 67        | 68        | 60         | 60       | 14.4        | 14.3       | n/a              | n/a               | n/a        | n/a        | n/a        | n/a        |
| 69        | 66        | 45         | 45       | 19.9        | 19.9       | Permitted        | Permitted         | n/a        | n/a        | n/a        | n/a        |
| 69        | 72        | 555        | 613      | 16.9        | 15.7       | n/a              | n/a               | n/a        | n/a        | n/a        | n/a        |
| 69        | 70        | 225        | 167      | 16.9        | 15.7       | n/a              | n/a               | n/a        | n/a        | n/a        | n/a        |
| 70        | 107       | 1021       | 606      | 15.3        | 14.9       | n/a              | n/a               | 2          | 2          | 0.77       | 0.43       |
| 71        | 68        | 225        | 225      | 36.5        | 37.7       | Permitted        | Permitted         | n/a        | n/a        | n/a        | n/a        |
| 71        | 66        | 225        | 330      | 17.5        | 18.6       | n/a              | n/a               | n/a        | n/a        | n/a        | n/a        |
| 71        | 72        | 53         | 45       | 17.5        | 18.6       | n/a              | n/a               | n/a        | n/a        | n/a        | n/a        |
| 72        | 61        | 982        | 969      | 30.5        | 30.5       | n/a              | n/a               | 2          | 2          | 0.69       | 0.65       |
| 73        | 78        | 267        | 345      | 35.9        | 39.9       | Permitted        | Permitted         | n/a        | n/a        | n/a        | n/a        |
| 73        | 76        | 492        | 481      | 17          | 15.3       | n/a              | n/a               | n/a        | n/a        | n/a        | n/a        |
| 73        | 74        | 291        | 224      | 17          | 15.3       | n/a              | n/a               | n/a        | n/a        | n/a        | n/a        |
| 74        | 39        | 1225       | 1021     | 15.5        | 15.3       | n/a              | n/a               | 2          | 2          | 0.85       | 0.72       |
| 75        | 80        | 104        | 90       | 17.4        | 16.2       | Permitted        | Permitted         | n/a        | n/a        | n/a        | n/a        |
| 75        | 78        | 481        | 437      | 6.4         | 6.6        | n/a              | n/a               | n/a        | n/a        | n/a        | n/a        |
| 75        | 76        | 117        | 120      | 6.4         | 6.6        | n/a              | n/a               | n/a        | n/a        | n/a        | n/a        |
| 76        | 81        | 726        | 808      | 45          | 45.2       | n/a              | n/a               | 2          | 2          | 0.63       | 0.64       |
| 77        | 74        | 351        | 290      | 21.6        | 22.9       | Permitted        | Permitted         | n/a        | n/a        | n/a        | n/a        |
| 77        | 80        | 527        | 540      | 11.4        | 7.3        | n/a              | n/a               | n/a        | n/a        | n/a        | n/a        |
| 77        | 78        | 131        | 285      | 11.4        | 7.3        | n/a              | n/a               | n/a        | n/a        | n/a        | n/a        |
| 78        | 115       | 879        | 1067     | 45.4        | 46         | n/a              | n/a               | 2          | 2          | 0.59       | 0.78       |
| 79        | 76        | 117        | 207      | 24.6        | 26.8       | Permitted        | Permitted         | n/a        | n/a        | n/a        | n/a        |
| 79        | 74        | 582        | 506      | 10.1        | 9.3        | n/a              | n/a               | n/a        | n/a        | n/a        | n/a        |

Table A (Continued)

|    |     |      |      |      |      |           |           |     |     |      |      |
|----|-----|------|------|------|------|-----------|-----------|-----|-----|------|------|
| 79 | 80  | 135  | 135  | 10.1 | 9.3  | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 81 | 86  | 45   | 45   | 50.5 | 59.9 | Permitted | Permitted | n/a | n/a | n/a  | n/a  |
| 81 | 84  | 559  | 643  | 11.7 | 11.4 | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 81 | 82  | 121  | 120  | 11.7 | 11.4 | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 82 | 47  | 669  | 720  | 15   | 15   | n/a       | n/a       | 2   | 2   | 0.44 | 0.47 |
| 83 | 88  | 48   | 90   | 26.8 | 26   | Permitted | Permitted | n/a | n/a | n/a  | n/a  |
| 83 | 86  | 370  | 388  | 13.4 | 12.5 | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 83 | 84  | 96   | 60   | 13.4 | 12.5 | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 84 | 89  | 905  | 931  | 30.3 | 30.4 | n/a       | n/a       | 2   | 2   | 0.66 | 0.61 |
| 85 | 82  | 250  | 255  | 34.3 | 35.5 | Permitted | Permitted | n/a | n/a | n/a  | n/a  |
| 85 | 88  | 872  | 980  | 10   | 9.4  | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 85 | 86  | 147  | 167  | 10   | 9.4  | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 86 | 123 | 562  | 600  | 44.6 | 44.7 | n/a       | n/a       | 2   | 2   | 0.50 | 0.43 |
| 87 | 84  | 250  | 228  | 14.9 | 15.6 | Permitted | Permitted | n/a | n/a | n/a  | n/a  |
| 87 | 82  | 297  | 345  | 8.6  | 8.8  | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 87 | 88  | 90   | 45   | 8.6  | 8.8  | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 88 | 77  | 1009 | 1115 | 45.8 | 46.1 | n/a       | n/a       | 2   | 2   | 0.65 | 0.70 |
| 89 | 94  | 129  | 45   | 53.9 | 52.2 | Permitted | Permitted | n/a | n/a | n/a  | n/a  |
| 89 | 92  | 652  | 718  | 9.5  | 9    | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 89 | 90  | 124  | 168  | 9.5  | 9    | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 90 | 55  | 819  | 750  | 15.1 | 15   | n/a       | n/a       | 2   | 2   | 0.64 | 0.58 |
| 91 | 96  | 260  | 196  | 17.4 | 22.9 | Permitted | Permitted | n/a | n/a | n/a  | n/a  |
| 91 | 94  | 629  | 815  | 7    | 9.2  | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 91 | 92  | 90   | 90   | 7    | 9.2  | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 92 | 97  | 858  | 808  | 60.5 | 60.3 | n/a       | n/a       | 2   | 2   | 0.69 | 0.53 |
| 93 | 90  | 362  | 225  | 35   | 43.3 | Permitted | Permitted | n/a | n/a | n/a  | n/a  |
| 93 | 96  | 801  | 1022 | 21.8 | 10.2 | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 93 | 94  | 86   | 186  | 21.8 | 10.2 | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 94 | 131 | 843  | 1046 | 45.3 | 45.9 | n/a       | n/a       | 2   | 2   | 0.55 | 0.81 |
| 95 | 92  | 116  | 0    | 37.7 | 53.8 | Permitted | Permitted | n/a | n/a | n/a  | n/a  |

Table A (Continued)

|     |     |      |      |      |      |           |            |     |     |      |      |
|-----|-----|------|------|------|------|-----------|------------|-----|-----|------|------|
| 95  | 90  | 333  | 357  | 10.3 | 14.3 | n/a       | n/a        | n/a | n/a | n/a  | n/a  |
| 95  | 96  | 208  | 185  | 10.3 | 14.3 | n/a       | n/a        | n/a | n/a | n/a  | n/a  |
| 96  | 85  | 1269 | 1403 | 31.1 | 31.3 | n/a       | n/a        | 2   | 2   | 0.77 | 0.86 |
| 97  | 102 | 0    | 0    | 92.2 | n/a  | Permitted | Prohibited | n/a | n/a | n/a  | n/a  |
| 97  | 100 | 650  | 630  | 18.2 | 16.1 | n/a       | n/a        | n/a | n/a | n/a  | n/a  |
| 97  | 98  | 209  | 178  | 18.2 | 16.1 | n/a       | n/a        | n/a | n/a | n/a  | n/a  |
| 98  | 63  | 765  | 750  | 15   | 15   | n/a       | n/a        | 2   | 2   | 0.56 | 0.51 |
| 99  | 104 | 96   | 166  | 31   | 30.2 | Permitted | Permitted  | n/a | n/a | n/a  | n/a  |
| 99  | 102 | 388  | 497  | 12.2 | 12.2 | n/a       | n/a        | n/a | n/a | n/a  | n/a  |
| 99  | 100 | 60   | 60   | 12.2 | 12.2 | n/a       | n/a        | n/a | n/a | n/a  | n/a  |
| 100 | 105 | 769  | 825  | 30.1 | 31.9 | n/a       | n/a        | 2   | 1   | 0.51 | 1.07 |
| 101 | 98  | 140  | 210  | 38.4 | 31.6 | Permitted | Permitted  | n/a | n/a | n/a  | n/a  |
| 101 | 104 | 967  | 1071 | 10.9 | 8.8  | n/a       | n/a        | n/a | n/a | n/a  | n/a  |
| 101 | 102 | 174  | 120  | 10.9 | 8.8  | n/a       | n/a        | n/a | n/a | n/a  | n/a  |
| 102 | 139 | 562  | 617  | 44.6 | 44.7 | n/a       | n/a        | 2   | 2   | 0.42 | 0.48 |
| 103 | 100 | 60   | 135  | 17.3 | 19.7 | Permitted | Permitted  | n/a | n/a | n/a  | n/a  |
| 103 | 98  | 417  | 362  | 7.9  | 6.7  | n/a       | n/a        | n/a | n/a | n/a  | n/a  |
| 103 | 104 | 187  | 195  | 7.9  | 6.7  | n/a       | n/a        | n/a | n/a | n/a  | n/a  |
| 104 | 93  | 1250 | 1432 | 62   | 62.8 | n/a       | n/a        | 2   | 2   | 0.80 | 0.92 |
| 105 | 110 | 80   | 0    | 40.2 | n/a  | Permitted | Prohibited | n/a | n/a | n/a  | n/a  |
| 105 | 108 | 682  | 735  | 9.8  | 19   | n/a       | n/a        | n/a | n/a | n/a  | n/a  |
| 105 | 106 | 8    | 90   | 9.8  | 19   | n/a       | n/a        | n/a | n/a | n/a  | n/a  |
| 106 | 71  | 504  | 600  | 14.8 | 14.9 | n/a       | n/a        | 2   | 2   | 0.38 | 0.44 |
| 107 | 112 | 218  | 261  | 20.1 | 17   | Permitted | Permitted  | n/a | n/a | n/a  | n/a  |
| 107 | 110 | 645  | 240  | 8.2  | 9    | n/a       | n/a        | n/a | n/a | n/a  | n/a  |
| 107 | 108 | 158  | 105  | 8.2  | 9    | n/a       | n/a        | n/a | n/a | n/a  | n/a  |
| 109 | 106 | 168  | 165  | 37.2 | 37.5 | Permitted | Permitted  | n/a | n/a | n/a  | n/a  |
| 109 | 112 | 792  | 795  | 17.9 | 15.9 | n/a       | n/a        | n/a | n/a | n/a  | n/a  |
| 109 | 110 | 135  | 135  | 17.9 | 15.9 | n/a       | n/a        | n/a | n/a | n/a  | n/a  |
| 110 | 147 | 860  | 375  | 45.4 | 44.1 | n/a       | n/a        | 2   | 2   | 0.60 | 0.47 |

Table A (Continued)

|            |            |             |             |             |             |            |            |          |          |             |             |
|------------|------------|-------------|-------------|-------------|-------------|------------|------------|----------|----------|-------------|-------------|
| 111        | 108        | 150         | 150         | 35.2        | 26          | Permitted  | Permitted  | n/a      | n/a      | n/a         | n/a         |
| 111        | 106        | 328         | 344         | 10.2        | 12.6        | n/a        | n/a        | n/a      | n/a      | n/a         | n/a         |
| 111        | 112        | 271         | 345         | 10.2        | 12.6        | n/a        | n/a        | n/a      | n/a      | n/a         | n/a         |
| <b>112</b> | <b>101</b> | <b>1281</b> | <b>1401</b> | <b>31.1</b> | <b>30.4</b> | <b>n/a</b> | <b>n/a</b> | <b>2</b> | <b>3</b> | <b>0.84</b> | <b>0.67</b> |
| 113        | 118        | 45          | 45          | 17.2        | 17.2        | Permitted  | Permitted  | n/a      | n/a      | n/a         | n/a         |
| 113        | 116        | 498         | 509         | 16.4        | 16.3        | n/a        | n/a        | n/a      | n/a      | n/a         | n/a         |
| 113        | 114        | 237         | 226         | 16.4        | 16.3        | n/a        | n/a        | n/a      | n/a      | n/a         | n/a         |
| 114        | 79         | 834         | 848         | 45.3        | 45.3        | n/a        | n/a        | 2        | 2        | 0.65        | 0.78        |
| 115        | 120        | 165         | 165         | 30.6        | 33.4        | Permitted  | Permitted  | n/a      | n/a      | n/a         | n/a         |
| 115        | 118        | 481         | 495         | 11          | 12.3        | n/a        | n/a        | n/a      | n/a      | n/a         | n/a         |
| 115        | 116        | 233         | 407         | 11          | 12.3        | n/a        | n/a        | n/a      | n/a      | n/a         | n/a         |
| 116        | 121        | 1020        | 1203        | 45.8        | 46.4        | n/a        | n/a        | 2        | 2        | 0.73        | 0.99        |
| 117        | 114        | 137         | 160         | 26.3        | 26.7        | Permitted  | Permitted  | n/a      | n/a      | n/a         | n/a         |
| 117        | 120        | 585         | 585         | 9.1         | 9           | n/a        | n/a        | n/a      | n/a      | n/a         | n/a         |
| 117        | 118        | 284         | 270         | 9.1         | 9           | n/a        | n/a        | n/a      | n/a      | n/a         | n/a         |
| 119        | 116        | 290         | 287         | 31.9        | 31.2        | Permitted  | Permitted  | n/a      | n/a      | n/a         | n/a         |
| 119        | 114        | 460         | 463         | 14.6        | 14.7        | n/a        | n/a        | n/a      | n/a      | n/a         | n/a         |
| 119        | 120        | 45          | 45          | 14.6        | 14.7        | n/a        | n/a        | n/a      | n/a      | n/a         | n/a         |
| 121        | 126        | 105         | 105         | 63.7        | 64.6        | Permitted  | Permitted  | n/a      | n/a      | n/a         | n/a         |
| 121        | 124        | 792         | 991         | 12.6        | 12.7        | n/a        | n/a        | n/a      | n/a      | n/a         | n/a         |
| 121        | 122        | 123         | 108         | 12.6        | 12.7        | n/a        | n/a        | n/a      | n/a      | n/a         | n/a         |
| 122        | 87         | 637         | 618         | 44.8        | 44.7        | n/a        | n/a        | 2        | 2        | 0.42        | 0.51        |
| 123        | 128        | 45          | 45          | 28.1        | 30.7        | Permitted  | Permitted  | n/a      | n/a      | n/a         | n/a         |
| 123        | 126        | 441         | 407         | 12          | 13          | n/a        | n/a        | n/a      | n/a      | n/a         | n/a         |
| 123        | 124        | 75          | 148         | 12          | 13          | n/a        | n/a        | n/a      | n/a      | n/a         | n/a         |
| 124        | 129        | 1096        | 1364        | 30.7        | 31.3        | n/a        | n/a        | 2        | 2        | 0.64        | 0.87        |
| 125        | 122        | 52          | 45          | 51          | 56.3        | Permitted  | Permitted  | n/a      | n/a      | n/a         | n/a         |
| 125        | 128        | 856         | 865         | 13.2        | 10.5        | n/a        | n/a        | n/a      | n/a      | n/a         | n/a         |
| 125        | 126        | 279         | 313         | 13.2        | 10.5        | n/a        | n/a        | n/a      | n/a      | n/a         | n/a         |
| 127        | 124        | 228         | 225         | 31.3        | 31.7        | Permitted  | Permitted  | n/a      | n/a      | n/a         | n/a         |

Table A (Continued)

|     |     |      |      |      |       |           |           |     |     |      |      |
|-----|-----|------|------|------|-------|-----------|-----------|-----|-----|------|------|
| 127 | 122 | 462  | 465  | 14.7 | 16.2  | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 127 | 128 | 105  | 105  | 14.7 | 16.2  | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 128 | 117 | 1006 | 1015 | 45.8 | 45.8  | n/a       | n/a       | 2   | 2   | 0.68 | 0.56 |
| 129 | 134 | 173  | 165  | 43.5 | 39.5  | Permitted | Permitted | n/a | n/a | n/a  | n/a  |
| 129 | 132 | 877  | 1156 | 8.2  | 9.6   | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 129 | 130 | 46   | 42   | 8.2  | 9.6   | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 130 | 95  | 657  | 543  | 44.8 | 44.5  | n/a       | n/a       | 2   | 2   | 0.45 | 0.43 |
| 131 | 136 | 146  | 298  | 24.1 | 24.8  | Permitted | Permitted | n/a | n/a | n/a  | n/a  |
| 131 | 134 | 512  | 525  | 7.1  | 7.3   | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 131 | 132 | 185  | 223  | 7.1  | 7.3   | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 132 | 137 | 1365 | 1770 | 62.5 | 64.3  | n/a       | n/a       | 2   | 2   | 0.82 | 1.13 |
| 133 | 130 | 2    | 0    | 81.6 | 168.1 | Permitted | Permitted | n/a | n/a | n/a  | n/a  |
| 133 | 136 | 858  | 720  | 19.4 | 18.6  | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 133 | 134 | 185  | 180  | 19.4 | 18.6  | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 135 | 132 | 303  | 390  | 34.6 | 39.9  | Permitted | Permitted | n/a | n/a | n/a  | n/a  |
| 135 | 130 | 609  | 500  | 15.8 | 15.5  | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 135 | 136 | 183  | 205  | 15.8 | 15.5  | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 136 | 125 | 1186 | 1222 | 30.9 | 31    | n/a       | n/a       | 2   | 2   | 0.97 | 0.86 |
| 137 | 142 | 481  | 328  | 34.1 | 43.6  | Permitted | Permitted | n/a | n/a | n/a  | n/a  |
| 137 | 140 | 748  | 1214 | 22.6 | 12.1  | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 137 | 138 | 137  | 227  | 22.6 | 12.1  | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 138 | 103 | 663  | 692  | 44.8 | 44.9  | n/a       | n/a       | 2   | 2   | 0.50 | 0.56 |
| 139 | 144 | 159  | 60   | 29.1 | 28.6  | Permitted | Permitted | n/a | n/a | n/a  | n/a  |
| 139 | 142 | 284  | 437  | 9.6  | 12.1  | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 139 | 140 | 119  | 120  | 9.6  | 12.1  | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 140 | 145 | 972  | 1439 | 30.5 | 31.4  | n/a       | n/a       | 2   | 2   | 0.61 | 0.86 |
| 141 | 138 | 64   | 0    | 42.1 | 128.1 | Permitted | Permitted | n/a | n/a | n/a  | n/a  |
| 141 | 144 | 644  | 600  | 10.8 | 10.8  | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 141 | 142 | 120  | 120  | 10.8 | 10.8  | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 143 | 140 | 105  | 105  | 21.4 | 21.9  | Permitted | Permitted | n/a | n/a | n/a  | n/a  |

Table A (Continued)

|     |     |      |     |      |      |           |           |     |     |      |      |
|-----|-----|------|-----|------|------|-----------|-----------|-----|-----|------|------|
| 143 | 138 | 463  | 465 | 15.7 | 15.8 | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 143 | 144 | 242  | 240 | 15.7 | 15.8 | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 144 | 133 | 1044 | 900 | 61.2 | 60.6 | n/a       | n/a       | 2   | 2   | 0.87 | 0.60 |
| 145 | 150 | 375  | 705 | 24.9 | 65.3 | Permitted | Permitted | n/a | n/a | n/a  | n/a  |
| 145 | 148 | 589  | 705 | 12.1 | 14.4 | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 145 | 146 | 8    | 29  | 12.1 | 14.4 | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 146 | 111 | 749  | 839 | 45.1 | 45.3 | n/a       | n/a       | 2   | 2   | 0.42 | 0.53 |
| 147 | 152 | 39   | 0   | 33.3 | 29.4 | Permitted | Permitted | n/a | n/a | n/a  | n/a  |
| 147 | 150 | 510  | 180 | 13.8 | 12.1 | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 147 | 148 | 311  | 195 | 13.8 | 12.1 | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 149 | 146 | 253  | 315 | 41.8 | 52.3 | Permitted | Permitted | n/a | n/a | n/a  | n/a  |
| 149 | 152 | 512  | 450 | 14.7 | 15.1 | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 149 | 150 | 60   | 60  | 14.7 | 15.1 | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 151 | 148 | 75   | 75  | 18.2 | 14.2 | Permitted | Permitted | n/a | n/a | n/a  | n/a  |
| 151 | 146 | 488  | 495 | 15.9 | 14.8 | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 151 | 152 | 277  | 270 | 15.9 | 14.8 | n/a       | n/a       | n/a | n/a | n/a  | n/a  |
| 152 | 141 | 827  | 720 | 30.2 | 30   | n/a       | n/a       | 2   | 2   | 0.58 | 0.71 |



## **APPENDIX B**

### **SUMMARY OF UTNDP RESULTS OF TEST NETWORK 4 UNDER THREE O-D PLANS**

**Table B** Summary of UTNDP Results Under Three O-D Plans

| Node     |        | O-D Plan 1 (Original) |            |           |            |           | O-D Plan 2 (50% of Original) |            |           |            |           | O-D Plan 3 (10% of Original) |            |           |            |           |
|----------|--------|-----------------------|------------|-----------|------------|-----------|------------------------------|------------|-----------|------------|-----------|------------------------------|------------|-----------|------------|-----------|
| Starting | Ending | Avg. Flow             | Avg. Delay | Left Turn | No. of Ln. | V/C Ratio | Avg. Flow                    | Avg. Delay | Left Turn | No. of Ln. | V/C Ratio | Avg. Flow                    | Avg. Delay | Left Turn | No. of Ln. | V/C Ratio |
| 33       | 38     | 287                   | 33.6       | Prmtd.    | N/a        | n/a       | 125                          | 19.2       | Prmtd.    | N/a        | n/a       | 14                           | 11.7       | Prmtd.    | N/a        | n/a       |
| 33       | 36     | 433                   | 14.3       | n/a       | n/a        | n/a       | 235                          | 12.3       | n/a       | n/a        | n/a       | 59                           | 11.9       | n/a       | n/a        | n/a       |
| 33       | 34     | 60                    | 14.3       | n/a       | n/a        | n/a       | 30                           | 12.3       | n/a       | n/a        | n/a       | 6                            | 11.9       | n/a       | n/a        | n/a       |
| 35       | 40     | 45                    | 26.5       | Prmtd.    | N/a        | n/a       | 23                           | 20.7       | Prmtd.    | N/a        | n/a       | 5                            | 17.5       | Prmtd.    | N/a        | n/a       |
| 35       | 38     | 315                   | 11.5       | n/a       | n/a        | n/a       | 188                          | 10.8       | n/a       | n/a        | n/a       | 14                           | 10.8       | n/a       | n/a        | n/a       |
| 35       | 36     | 420                   | 11.5       | n/a       | n/a        | n/a       | 180                          | 10.8       | n/a       | n/a        | n/a       | 60                           | 10.8       | n/a       | n/a        | n/a       |
| 36       | 41     | 1154                  | 46.2       | n/a       | 2          | 0.85      | 507                          | 44.4       | n/a       | 2          | 0.47      | 119                          | 43.5       | n/a       | 2          | 0.12      |
| 37       | 34     | 315                   | 28.5       | Prmtd.    | N/a        | n/a       | 135                          | 20.7       | Prmtd.    | N/a        | n/a       | 27                           | 15.6       | Prmtd.    | N/a        | n/a       |
| 37       | 40     | 510                   | 15.6       | n/a       | n/a        | n/a       | 298                          | 10.4       | n/a       | n/a        | n/a       | 58                           | 9.5        | n/a       | n/a        | n/a       |
| 37       | 38     | 45                    | 15.6       | n/a       | n/a        | n/a       | 89                           | 10.4       | n/a       | n/a        | n/a       | 28                           | 9.5        | n/a       | n/a        | n/a       |
| 38       | 75     | 647                   | 14.9       | n/a       | 2          | 0.51      | 401                          | 14.7       | n/a       | 2          | 0.33      | 55                           | 14.4       | n/a       | 2          | 0.05      |
| 39       | 36     | 301                   | 33.9       | Prmtd.    | N/a        | n/a       | 92                           | 20.1       | Prmtd.    | N/a        | n/a       | 0                            | 18.2       | Prmtd.    | N/a        | n/a       |
| 39       | 34     | 450                   | 13.4       | n/a       | n/a        | n/a       | 248                          | 11.1       | n/a       | n/a        | n/a       | 50                           | 11.4       | n/a       | n/a        | n/a       |
| 39       | 40     | 270                   | 13.4       | n/a       | n/a        | n/a       | 92                           | 11.1       | n/a       | n/a        | n/a       | 20                           | 11.4       | n/a       | n/a        | n/a       |
| 41       | 46     | 133                   | 27         | Prmtd.    | N/a        | n/a       | 91                           | 12.5       | Prmtd.    | N/a        | n/a       | 11                           | 9.7        | Prmtd.    | N/a        | n/a       |
| 41       | 44     | 916                   | 7.4        | n/a       | n/a        | n/a       | 364                          | 5.8        | n/a       | n/a        | n/a       | 98                           | 5.8        | n/a       | n/a        | n/a       |
| 41       | 42     | 105                   | 7.4        | n/a       | n/a        | n/a       | 53                           | 5.8        | n/a       | n/a        | n/a       | 11                           | 5.8        | n/a       | n/a        | n/a       |
| 43       | 48     | 90                    | 28.4       | Prmtd.    | N/a        | n/a       | 112                          | 19.3       | Prmtd.    | N/a        | n/a       | 23                           | 11.7       | Prmtd.    | N/a        | n/a       |
| 43       | 46     | 360                   | 16.6       | n/a       | n/a        | n/a       | 135                          | 12.5       | n/a       | n/a        | n/a       | 5                            | 11.8       | n/a       | n/a        | n/a       |
| 43       | 44     | 300                   | 16.6       | n/a       | n/a        | n/a       | 128                          | 12.5       | n/a       | n/a        | n/a       | 48                           | 11.8       | n/a       | n/a        | n/a       |
| 44       | 49     | 1335                  | 31.2       | n/a       | 2          | 0.84      | 673                          | 29.9       | n/a       | 2          | 0.53      | 213                          | 29.1       | n/a       | 2          | 0.16      |
| 45       | 42     | 225                   | 38.4       | Prmtd.    | N/a        | n/a       | 125                          | 17.9       | Prmtd.    | N/a        | n/a       | 23                           | 11.7       | Prmtd.    | N/a        | n/a       |
| 45       | 48     | 690                   | 14.1       | n/a       | n/a        | n/a       | 387                          | 8          | n/a       | n/a        | n/a       | 80                           | 6.9        | n/a       | n/a        | n/a       |
| 45       | 46     | 45                    | 14.1       | n/a       | n/a        | n/a       | 0                            | 8          | n/a       | n/a        | n/a       | 0                            | 6.9        | n/a       | n/a        | n/a       |
| 46       | 83     | 538                   | 14.8       | n/a       | 2          | 0.38      | 226                          | 14.6       | n/a       | 2          | 0.23      | 15                           | 14.4       | n/a       | 2          | 0.05      |
| 47       | 44     | 120                   | 35.3       | Prmtd.    | N/a        | n/a       | 182                          | 12.3       | Prmtd.    | N/a        | n/a       | 68                           | 6.7        | Prmtd.    | N/a        | n/a       |
| 47       | 42     | 510                   | 5.7        | n/a       | n/a        | n/a       | 243                          | 6.8        | n/a       | n/a        | n/a       | 50                           | 6.1        | n/a       | n/a        | n/a       |

Table B (Continued)

|           |           |      |      |        |     |      |          |            |                |            |            |     |      |        |     |      |
|-----------|-----------|------|------|--------|-----|------|----------|------------|----------------|------------|------------|-----|------|--------|-----|------|
| 47        | 48        | 90   | 5.7  | n/a    | n/a | n/a  | 23       | 6.8        | n/a            | n/a        | n/a        | 11  | 6.1  | n/a    | n/a | n/a  |
| 48        | 37        | 870  | 45.4 | n/a    | 2   | 0.55 | 522      | 44.5       | n/a            | 2          | 0.31       | 113 | 43.5 | n/a    | 2   | 0.11 |
| <b>49</b> | <b>54</b> | 150  | 37.5 | Prmtd. | N/a | n/a  | <b>0</b> | <b>n/a</b> | <b>Prhted.</b> | <b>N/a</b> | <b>n/a</b> | 68  | 11.1 | Prmtd. | N/a | n/a  |
| 49        | 52        | 1035 | 10.1 | n/a    | n/a | n/a  | 531      | 10.1       | n/a            | n/a        | n/a        | 110 | 6.7  | n/a    | n/a | n/a  |
| 49        | 50        | 150  | 10.1 | n/a    | n/a | n/a  | 143      | 10.1       | n/a            | n/a        | n/a        | 36  | 6.7  | n/a    | n/a | n/a  |
| 51        | 56        | 195  | 30.3 | Prmtd. | N/a | n/a  | 98       | 15.5       | Prmtd.         | N/a        | n/a        | 28  | 11.3 | Prmtd. | N/a | n/a  |
| 51        | 54        | 688  | 17.4 | n/a    | n/a | n/a  | 368      | 13.2       | n/a            | n/a        | n/a        | 56  | 11.5 | n/a    | n/a | n/a  |
| 51        | 52        | 287  | 17.4 | n/a    | n/a | n/a  | 120      | 13.2       | n/a            | n/a        | n/a        | 33  | 11.5 | n/a    | n/a | n/a  |
| 52        | 57        | 1502 | 63.1 | n/a    | 2   | 1.10 | 651      | 59.7       | n/a            | 2          | 0.48       | 143 | 58   | n/a    | 2   | 0.11 |
| 53        | 50        | 150  | 92.1 | Prmtd. | N/a | n/a  | 75       | 35.7       | Prmtd.         | N/a        | n/a        | 15  | 19.7 | Prmtd. | N/a | n/a  |
| 53        | 56        | 705  | 10   | n/a    | n/a | n/a  | 384      | 14.1       | n/a            | n/a        | n/a        | 74  | 11.5 | n/a    | n/a | n/a  |
| 53        | 54        | 263  | 10   | n/a    | n/a | n/a  | 183      | 14.1       | n/a            | n/a        | n/a        | 73  | 11.5 | n/a    | n/a | n/a  |
| 54        | 91        | 1101 | 15.4 | n/a    | 2   | 0.73 | 550      | 14.8       | n/a            | 2          | 0.42       | 196 | 14.6 | n/a    | 2   | 0.15 |
| 55        | 52        | 180  | 44.3 | Prmtd. | N/a | n/a  | 0        | 26         | Prmtd.         | N/a        | n/a        | 0   | 18.6 | Prmtd. | N/a | n/a  |
| 55        | 50        | 510  | 10.2 | n/a    | n/a | n/a  | 188      | 12.2       | n/a            | n/a        | n/a        | 30  | 11.4 | n/a    | n/a | n/a  |
| 55        | 56        | 60   | 10.2 | n/a    | n/a | n/a  | 30       | 12.2       | n/a            | n/a        | n/a        | 0   | 11.4 | n/a    | n/a | n/a  |
| 56        | 45        | 960  | 30.4 | n/a    | 2   | 0.65 | 512      | 29.6       | n/a            | 2          | 0.37       | 103 | 29   | n/a    | 2   | 0.06 |
| 57        | 62        | 212  | 38.6 | Prmtd. | N/a | n/a  | 99       | 18.5       | Prmtd.         | N/a        | n/a        | 0   | 16   | Prmtd. | N/a | n/a  |
| 57        | 60        | 1095 | 8.4  | n/a    | n/a | n/a  | 434      | 8.2        | n/a            | n/a        | n/a        | 110 | 9.4  | n/a    | n/a | n/a  |
| 57        | 58        | 196  | 8.4  | n/a    | n/a | n/a  | 117      | 8.2        | n/a            | n/a        | n/a        | 33  | 9.4  | n/a    | n/a | n/a  |
| 59        | 64        | 254  | 40.9 | Prmtd. | N/a | n/a  | 189      | 20.4       | Prmtd.         | N/a        | n/a        | 48  | 12.8 | Prmtd. | N/a | n/a  |
| 59        | 62        | 451  | 18.8 | n/a    | n/a | n/a  | 164      | 12.3       | n/a            | n/a        | n/a        | 5   | 12.6 | n/a    | n/a | n/a  |
| 59        | 60        | 120  | 18.8 | n/a    | n/a | n/a  | 60       | 12.3       | n/a            | n/a        | n/a        | 30  | 12.6 | n/a    | n/a | n/a  |
| 60        | 65        | 1336 | 31.2 | n/a    | 2   | 0.64 | 703      | 30         | n/a            | 2          | 0.50       | 191 | 29.1 | n/a    | 2   | 0.12 |
| 61        | 58        | 105  | 38.2 | Prmtd. | N/a | n/a  | 107      | 12.8       | Prmtd.         | N/a        | n/a        | 20  | 7.2  | Prmtd. | N/a | n/a  |
| 61        | 64        | 804  | 3.9  | n/a    | n/a | n/a  | 424      | 5.6        | n/a            | n/a        | n/a        | 105 | 4.2  | n/a    | n/a | n/a  |
| 61        | 62        | 60   | 3.9  | n/a    | n/a | n/a  | 39       | 5.6        | n/a            | n/a        | n/a        | 12  | 4.2  | n/a    | n/a | n/a  |
| 62        | 99        | 723  | 15   | n/a    | 2   | 0.59 | 302      | 14.6       | n/a            | 2          | 0.31       | 17  | 14.4 | n/a    | 2   | 0.05 |
| 63        | 60        | 121  | 28.3 | Prmtd. | N/a | n/a  | 208      | 10.2       | Prmtd.         | N/a        | n/a        | 51  | 7    | Prmtd. | N/a | n/a  |
| 63        | 58        | 569  | 10.5 | n/a    | n/a | n/a  | 211      | 6.7        | n/a            | n/a        | n/a        | 34  | 7    | n/a    | n/a | n/a  |

**Table B (Continued)**

|           |           |          |            |                |            |            |          |            |                |            |            |     |      |        |     |      |
|-----------|-----------|----------|------------|----------------|------------|------------|----------|------------|----------------|------------|------------|-----|------|--------|-----|------|
| 63        | 64        | 60       | 10.5       | n/a            | n/a        | n/a        | 30       | 6.7        | n/a            | n/a        | n/a        | 9   | 7    | n/a    | n/a | n/a  |
| 64        | 53        | 1118     | 61.5       | n/a            | 2          | 0.74       | 642      | 59.7       | n/a            | 2          | 0.38       | 162 | 58.1 | n/a    | 2   | 0.11 |
| <b>65</b> | <b>70</b> | <b>0</b> | <b>n/a</b> | <b>Prhted.</b> | <b>N/a</b> | <b>n/a</b> | <b>0</b> | <b>n/a</b> | <b>Prhted.</b> | <b>N/a</b> | <b>n/a</b> | 45  | 6    | Prmtd. | N/a | n/a  |
| 65        | 68        | 750      | 12.3       | n/a            | n/a        | n/a        | 375      | 7.3        | n/a            | n/a        | n/a        | 75  | 3.6  | n/a    | n/a | n/a  |
| 65        | 66        | 586      | 12.3       | n/a            | n/a        | n/a        | 328      | 7.3        | n/a            | n/a        | n/a        | 71  | 3.6  | n/a    | n/a | n/a  |
| 67        | 72        | 310      | 28.1       | Prmtd.         | N/a        | n/a        | 153      | 17         | Prmtd.         | N/a        | n/a        | 57  | 13.8 | Prmtd. | N/a | n/a  |
| 67        | 70        | 440      | 14.3       | n/a            | n/a        | n/a        | 222      | 12.2       | n/a            | n/a        | n/a        | 18  | 13.4 | n/a    | n/a | n/a  |
| 67        | 68        | 60       | 14.3       | n/a            | n/a        | n/a        | 30       | 12.2       | n/a            | n/a        | n/a        | 6   | 13.4 | n/a    | n/a | n/a  |
| 69        | 66        | 45       | 19.9       | Prmtd.         | N/a        | n/a        | 23       | 23         | Prmtd.         | N/a        | n/a        | 5   | 15.2 | Prmtd. | N/a | n/a  |
| 69        | 72        | 613      | 15.7       | n/a            | n/a        | n/a        | 284      | 10.7       | n/a            | n/a        | n/a        | 62  | 9.1  | n/a    | n/a | n/a  |
| 69        | 70        | 167      | 15.7       | n/a            | n/a        | n/a        | 106      | 10.7       | n/a            | n/a        | n/a        | 17  | 9.1  | n/a    | n/a | n/a  |
| 70        | 107       | 606      | 14.9       | n/a            | 2          | 0.43       | 328      | 14.7       | n/a            | 2          | 0.31       | 80  | 14.5 | n/a    | 2   | 0.08 |
| 71        | 68        | 225      | 37.7       | Prmtd.         | N/a        | n/a        | 113      | 14.3       | Prmtd.         | N/a        | n/a        | 23  | 13.3 | Prmtd. | N/a | n/a  |
| 71        | 66        | 330      | 18.6       | n/a            | n/a        | n/a        | 130      | 7.4        | n/a            | n/a        | n/a        | 21  | 8.3  | n/a    | n/a | n/a  |
| 71        | 72        | 45       | 18.6       | n/a            | n/a        | n/a        | 133      | 7.4        | n/a            | n/a        | n/a        | 18  | 8.3  | n/a    | n/a | n/a  |
| 72        | 61        | 969      | 30.5       | n/a            | 2          | 0.65       | 570      | 29.7       | n/a            | 2          | 0.47       | 137 | 29   | n/a    | 2   | 0.09 |
| 73        | 78        | 345      | 39.9       | Prmtd.         | N/a        | n/a        | 116      | 17         | Prmtd.         | N/a        | n/a        | 19  | 11.2 | Prmtd. | N/a | n/a  |
| 73        | 76        | 481      | 15.3       | n/a            | n/a        | n/a        | 342      | 13.3       | n/a            | n/a        | n/a        | 72  | 11.4 | n/a    | n/a | n/a  |
| 73        | 74        | 224      | 15.3       | n/a            | n/a        | n/a        | 68       | 13.3       | n/a            | n/a        | n/a        | 14  | 11.4 | n/a    | n/a | n/a  |
| 74        | 39        | 1021     | 15.3       | n/a            | 2          | 0.72       | 431      | 14.7       | n/a            | 2          | 0.32       | 69  | 14.5 | n/a    | 2   | 0.06 |
| 75        | 80        | 90       | 16.2       | Prmtd.         | N/a        | n/a        | 68       | 10.3       | Prmtd.         | N/a        | n/a        | 14  | 8.5  | Prmtd. | N/a | n/a  |
| 75        | 78        | 437      | 6.6        | n/a            | n/a        | n/a        | 243      | 5.7        | n/a            | n/a        | n/a        | 41  | 5.3  | n/a    | n/a | n/a  |
| 75        | 76        | 120      | 6.6        | n/a            | n/a        | n/a        | 90       | 5.7        | n/a            | n/a        | n/a        | 0   | 5.3  | n/a    | n/a | n/a  |
| 76        | 81        | 808      | 45.2       | n/a            | 2          | 0.64       | 432      | 44.2       | n/a            | 2          | 0.40       | 72  | 43.4 | n/a    | 2   | 0.06 |
| 77        | 74        | 290      | 22.9       | Prmtd.         | N/a        | n/a        | 182      | 13.5       | Prmtd.         | N/a        | n/a        | 38  | 8.3  | Prmtd. | N/a | n/a  |
| 77        | 80        | 540      | 7.3        | n/a            | n/a        | n/a        | 270      | 5.3        | n/a            | n/a        | n/a        | 54  | 5    | n/a    | n/a | n/a  |
| 77        | 78        | 285      | 7.3        | n/a            | n/a        | n/a        | 121      | 5.3        | n/a            | n/a        | n/a        | 43  | 5    | n/a    | n/a | n/a  |
| 78        | 115       | 1067     | 46         | n/a            | 2          | 0.78       | 480      | 44.4       | n/a            | 2          | 0.34       | 103 | 43.4 | n/a    | 2   | 0.09 |
| 79        | 76        | 207      | 26.8       | Prmtd.         | N/a        | n/a        | 0        | 28.1       | Prmtd.         | N/a        | n/a        | 0   | 25.2 | Prmtd. | N/a | n/a  |
| 79        | 74        | 506      | 9.3        | n/a            | n/a        | n/a        | 182      | 14.8       | n/a            | n/a        | n/a        | 18  | 15.6 | n/a    | n/a | n/a  |

Table B (Continued)

|    |     |      |      |        |     |      |     |      |        |     |      |     |      |        |     |      |
|----|-----|------|------|--------|-----|------|-----|------|--------|-----|------|-----|------|--------|-----|------|
| 79 | 80  | 135  | 9.3  | n/a    | n/a | n/a  | 45  | 14.8 | n/a    | n/a | n/a  | 9   | 15.6 | n/a    | n/a | n/a  |
| 81 | 86  | 45   | 59.9 | Prmtd. | N/a | n/a  | 23  | 29.2 | Prmtd. | N/a | n/a  | 0   | 19.1 | Prmtd. | N/a | n/a  |
| 81 | 84  | 643  | 11.4 | n/a    | n/a | n/a  | 332 | 11.6 | n/a    | n/a | n/a  | 32  | 11.1 | n/a    | n/a | n/a  |
| 81 | 82  | 120  | 11.4 | n/a    | n/a | n/a  | 78  | 11.6 | n/a    | n/a | n/a  | 41  | 11.1 | n/a    | n/a | n/a  |
| 82 | 47  | 720  | 15   | n/a    | 2   | 0.47 | 447 | 14.8 | n/a    | 2   | 0.30 | 129 | 14.5 | n/a    | 2   | 0.10 |
| 83 | 88  | 90   | 26   | Prmtd. | N/a | n/a  | 0   | 24.3 | Prmtd. | N/a | n/a  | 0   | 19.1 | Prmtd. | N/a | n/a  |
| 83 | 86  | 388  | 12.5 | n/a    | n/a | n/a  | 169 | 12.2 | n/a    | n/a | n/a  | 15  | 11.6 | n/a    | n/a | n/a  |
| 83 | 84  | 60   | 12.5 | n/a    | n/a | n/a  | 57  | 12.2 | n/a    | n/a | n/a  | 0   | 11.6 | n/a    | n/a | n/a  |
| 84 | 89  | 931  | 30.4 | n/a    | 2   | 0.61 | 486 | 29.6 | n/a    | 2   | 0.35 | 32  | 28.8 | n/a    | 2   | 0.03 |
| 85 | 82  | 255  | 35.5 | Prmtd. | N/a | n/a  | 78  | 18.5 | Prmtd. | N/a | n/a  | 22  | 12.9 | Prmtd. | N/a | n/a  |
| 85 | 88  | 980  | 9.4  | n/a    | n/a | n/a  | 528 | 9    | n/a    | n/a | n/a  | 126 | 8    | n/a    | n/a | n/a  |
| 85 | 86  | 167  | 9.4  | n/a    | n/a | n/a  | 60  | 9    | n/a    | n/a | n/a  | 29  | 8    | n/a    | n/a | n/a  |
| 86 | 123 | 600  | 44.7 | n/a    | 2   | 0.43 | 252 | 43.8 | n/a    | 2   | 0.23 | 44  | 43.3 | n/a    | 2   | 0.04 |
| 87 | 84  | 228  | 15.6 | Prmtd. | N/a | n/a  | 97  | 10.4 | Prmtd. | N/a | n/a  | 0   | 9.7  | Prmtd. | N/a | n/a  |
| 87 | 82  | 345  | 8.8  | n/a    | n/a | n/a  | 292 | 5.8  | n/a    | n/a | n/a  | 66  | 6.1  | n/a    | n/a | n/a  |
| 87 | 88  | 45   | 8.8  | n/a    | n/a | n/a  | 45  | 5.8  | n/a    | n/a | n/a  | 9   | 6.1  | n/a    | n/a | n/a  |
| 88 | 77  | 1115 | 46.1 | n/a    | 2   | 0.70 | 573 | 44.6 | n/a    | 2   | 0.42 | 135 | 43.5 | n/a    | 2   | 0.10 |
| 89 | 94  | 45   | 52.2 | Prmtd. | N/a | n/a  | 116 | 22.1 | Prmtd. | N/a | n/a  | 24  | 8.5  | Prmtd. | N/a | n/a  |
| 89 | 92  | 718  | 9    | n/a    | n/a | n/a  | 333 | 7.4  | n/a    | n/a | n/a  | 8   | 8.4  | n/a    | n/a | n/a  |
| 89 | 90  | 168  | 9    | n/a    | n/a | n/a  | 38  | 7.4  | n/a    | n/a | n/a  | 0   | 8.4  | n/a    | n/a | n/a  |
| 90 | 55  | 750  | 15   | n/a    | 2   | 0.58 | 218 | 14.6 | n/a    | 2   | 0.19 | 30  | 14.4 | n/a    | 2   | 0.06 |
| 91 | 96  | 196  | 22.9 | Prmtd. | N/a | n/a  | 84  | 10.2 | Prmtd. | N/a | n/a  | 76  | 8.3  | Prmtd. | N/a | n/a  |
| 91 | 94  | 815  | 9.2  | n/a    | n/a | n/a  | 421 | 6.2  | n/a    | n/a | n/a  | 120 | 5.2  | n/a    | n/a | n/a  |
| 91 | 92  | 90   | 9.2  | n/a    | n/a | n/a  | 45  | 6.2  | n/a    | n/a | n/a  | 0   | 5.2  | n/a    | n/a | n/a  |
| 92 | 97  | 808  | 60.3 | n/a    | 2   | 0.53 | 378 | 58.8 | n/a    | 2   | 0.31 | 8   | 57.6 | n/a    | 2   | 0.02 |
| 93 | 90  | 225  | 43.3 | Prmtd. | N/a | n/a  | 113 | 17.8 | Prmtd. | N/a | n/a  | 23  | 11.5 | Prmtd. | N/a | n/a  |
| 93 | 96  | 1022 | 10.2 | n/a    | n/a | n/a  | 514 | 8.6  | n/a    | n/a | n/a  | 87  | 7.3  | n/a    | n/a | n/a  |
| 93 | 94  | 186  | 10.2 | n/a    | n/a | n/a  | 104 | 8.6  | n/a    | n/a | n/a  | 8   | 7.3  | n/a    | n/a | n/a  |
| 94 | 131 | 1046 | 45.9 | n/a    | 2   | 0.81 | 640 | 44.8 | n/a    | 2   | 0.42 | 152 | 43.6 | n/a    | 2   | 0.09 |
| 95 | 92  | 0    | 53.8 | Prmtd. | N/a | n/a  | 0   | 25.8 | Prmtd. | N/a | n/a  | 0   | 19.7 | Prmtd. | N/a | n/a  |

**Table B (Continued)**

|            |            |            |             |                |            |             |            |             |               |            |             |           |             |               |            |             |
|------------|------------|------------|-------------|----------------|------------|-------------|------------|-------------|---------------|------------|-------------|-----------|-------------|---------------|------------|-------------|
| 95         | 90         | 357        | 14.3        | n/a            | n/a        | n/a         | 68         | 11.5        | n/a           | n/a        | n/a         | 8         | 11.5        | n/a           | n/a        | n/a         |
| 95         | 96         | 185        | 14.3        | n/a            | n/a        | n/a         | 68         | 11.5        | n/a           | n/a        | n/a         | 14        | 11.5        | n/a           | n/a        | n/a         |
| 96         | 85         | 1403       | 31.3        | n/a            | 2          | 0.86        | 666        | 29.9        | n/a           | 2          | 0.42        | 176       | 29.1        | n/a           | 2          | 0.10        |
| <b>97</b>  | <b>102</b> | <b>0</b>   | <b>n/a</b>  | <b>Prhted.</b> | <b>N/a</b> | <b>n/a</b>  | <b>0</b>   | <b>38</b>   | <b>Prmtd.</b> | <b>N/a</b> | <b>n/a</b>  | <b>0</b>  | <b>23.7</b> | <b>Prmtd.</b> | <b>N/a</b> | <b>n/a</b>  |
| 97         | 100        | 630        | 16.1        | n/a            | n/a        | n/a         | 316        | 15.3        | n/a           | n/a        | n/a         | 8         | 14.5        | n/a           | n/a        | n/a         |
| 97         | 98         | 178        | 16.1        | n/a            | n/a        | n/a         | 62         | 15.3        | n/a           | n/a        | n/a         | 0         | 14.5        | n/a           | n/a        | n/a         |
| 98         | 63         | 750        | 15          | n/a            | 2          | 0.51        | 449        | 14.8        | n/a           | 2          | 0.32        | 94        | 14.5        | n/a           | 2          | 0.05        |
| 99         | 104        | 166        | 30.2        | Prmtd.         | N/a        | n/a         | 51         | 22.3        | Prmtd.        | N/a        | n/a         | 0         | 18.6        | Prmtd.        | N/a        | n/a         |
| 99         | 102        | 497        | 12.2        | n/a            | n/a        | n/a         | 205        | 10.5        | n/a           | n/a        | n/a         | 17        | 11          | n/a           | n/a        | n/a         |
| 99         | 100        | 60         | 12.2        | n/a            | n/a        | n/a         | 47         | 10.5        | n/a           | n/a        | n/a         | 0         | 11          | n/a           | n/a        | n/a         |
| <b>100</b> | <b>105</b> | <b>825</b> | <b>31.9</b> | <b>n/a</b>     | <b>1</b>   | <b>1.07</b> | <b>430</b> | <b>29.5</b> | <b>n/a</b>    | <b>2</b>   | <b>0.28</b> | <b>41</b> | <b>28.9</b> | <b>n/a</b>    | <b>2</b>   | <b>0.02</b> |
| 101        | 98         | 210        | 31.6        | Prmtd.         | N/a        | n/a         | 20         | 19.3        | Prmtd.        | N/a        | n/a         | 0         | 13.7        | Prmtd.        | N/a        | n/a         |
| 101        | 104        | 1071       | 8.8         | n/a            | n/a        | n/a         | 514        | 9.5         | n/a           | n/a        | n/a         | 56        | 8.7         | n/a           | n/a        | n/a         |
| 101        | 102        | 120        | 8.8         | n/a            | n/a        | n/a         | 51         | 9.5         | n/a           | n/a        | n/a         | 6         | 8.7         | n/a           | n/a        | n/a         |
| 102        | 139        | 617        | 44.7        | n/a            | 2          | 0.48        | 255        | 43.8        | n/a           | 2          | 0.21        | 23        | 43.3        | n/a           | 2          | 0.03        |
| 103        | 100        | 135        | 19.7        | Prmtd.         | N/a        | n/a         | 68         | 12.1        | Prmtd.        | N/a        | n/a         | 33        | 8.3         | Prmtd.        | N/a        | n/a         |
| 103        | 98         | 362        | 6.7         | n/a            | n/a        | n/a         | 366        | 6.6         | n/a           | n/a        | n/a         | 94        | 5.2         | n/a           | n/a        | n/a         |
| 103        | 104        | 195        | 6.7         | n/a            | n/a        | n/a         | 165        | 6.6         | n/a           | n/a        | n/a         | 60        | 5.2         | n/a           | n/a        | n/a         |
| 104        | 93         | 1432       | 62.8        | n/a            | 2          | 0.92        | 730        | 60          | n/a           | 2          | 0.53        | 117       | 58          | n/a           | 2          | 0.11        |
| <b>105</b> | <b>110</b> | <b>0</b>   | <b>n/a</b>  | <b>Prhted.</b> | <b>N/a</b> | <b>n/a</b>  | <b>38</b>  | <b>19</b>   | <b>Prmtd.</b> | <b>N/a</b> | <b>n/a</b>  | <b>0</b>  | <b>14.1</b> | <b>Prmtd.</b> | <b>N/a</b> | <b>n/a</b>  |
| 105        | 108        | 735        | 19          | n/a            | n/a        | n/a         | 368        | 9           | n/a           | n/a        | n/a         | 41        | 8.6         | n/a           | n/a        | n/a         |
| 105        | 106        | 90         | 19          | n/a            | n/a        | n/a         | 25         | 9           | n/a           | n/a        | n/a         | 0         | 8.6         | n/a           | n/a        | n/a         |
| 106        | 71         | 600        | 14.9        | n/a            | 2          | 0.44        | 376        | 14.7        | n/a           | 2          | 0.32        | 62        | 14.4        | n/a           | 2          | 0.04        |
| 107        | 112        | 261        | 17          | Prmtd.         | N/a        | n/a         | 155        | 10.9        | Prmtd.        | N/a        | n/a         | 0         | 11.4        | Prmtd.        | N/a        | n/a         |
| 107        | 110        | 240        | 9           | n/a            | n/a        | n/a         | 120        | 7           | n/a           | n/a        | n/a         | 36        | 7.1         | n/a           | n/a        | n/a         |
| 107        | 108        | 105        | 9           | n/a            | n/a        | n/a         | 53         | 7           | n/a           | n/a        | n/a         | 44        | 7.1         | n/a           | n/a        | n/a         |
| 109        | 106        | 165        | 37.5        | Prmtd.         | N/a        | n/a         | 128        | 19          | Prmtd.        | N/a        | n/a         | 34        | 11.4        | Prmtd.        | N/a        | n/a         |
| 109        | 112        | 795        | 15.9        | n/a            | n/a        | n/a         | 352        | 13          | n/a           | n/a        | n/a         | 62        | 11.4        | n/a           | n/a        | n/a         |
| 109        | 110        | 135        | 15.9        | n/a            | n/a        | n/a         | 68         | 13          | n/a           | n/a        | n/a         | 14        | 11.4        | n/a           | n/a        | n/a         |
| 110        | 147        | 375        | 44.1        | n/a            | 2          | 0.47        | 225        | 43.7        | n/a           | 2          | 0.21        | 50        | 43.3        | n/a           | 2          | 0.05        |

Table B (Continued)

|            |            |             |             |            |          |             |     |      |        |     |      |     |      |        |     |      |
|------------|------------|-------------|-------------|------------|----------|-------------|-----|------|--------|-----|------|-----|------|--------|-----|------|
| 111        | 108        | 150         | 26          | Prmtd.     | N/a      | n/a         | 75  | 18.4 | Prmtd. | N/a | n/a  | 15  | 15.1 | Prmtd. | N/a | n/a  |
| 111        | 106        | 344         | 12.6        | n/a        | n/a      | n/a         | 222 | 10.7 | n/a    | n/a | n/a  | 28  | 9.3  | n/a    | n/a | n/a  |
| 111        | 112        | 345         | 12.6        | n/a        | n/a      | n/a         | 78  | 10.7 | n/a    | n/a | n/a  | 0   | 9.3  | n/a    | n/a | n/a  |
| <b>112</b> | <b>101</b> | <b>1401</b> | <b>30.4</b> | <b>n/a</b> | <b>3</b> | <b>0.67</b> | 585 | 29.8 | n/a    | 2   | 0.39 | 62  | 28.9 | n/a    | 2   | 0.04 |
| 113        | 118        | 45          | 17.2        | Prmtd.     | N/a      | n/a         | 23  | 21   | Prmtd. | N/a | n/a  | 5   | 14.1 | Prmtd. | N/a | n/a  |
| 113        | 116        | 509         | 16.3        | n/a        | n/a      | n/a         | 300 | 10.8 | n/a    | n/a | n/a  | 60  | 8.8  | n/a    | n/a | n/a  |
| 113        | 114        | 226         | 16.3        | n/a        | n/a      | n/a         | 68  | 10.8 | n/a    | n/a | n/a  | 14  | 8.8  | n/a    | n/a | n/a  |
| 114        | 79         | 848         | 45.3        | n/a        | 2        | 0.78        | 227 | 43.7 | n/a    | 2   | 0.23 | 27  | 43.3 | n/a    | 2   | 0.06 |
| 115        | 120        | 165         | 33.4        | Prmtd.     | N/a      | n/a         | 105 | 17.6 | Prmtd. | N/a | n/a  | 50  | 12.7 | Prmtd. | N/a | n/a  |
| 115        | 118        | 495         | 12.3        | n/a        | n/a      | n/a         | 248 | 9.9  | n/a    | n/a | n/a  | 50  | 12.7 | n/a    | n/a | n/a  |
| 115        | 116        | 407         | 12.3        | n/a        | n/a      | n/a         | 128 | 9.9  | n/a    | n/a | n/a  | 4   | 12.7 | n/a    | n/a | n/a  |
| 116        | 121        | 1203        | 46.4        | n/a        | 2        | 0.99        | 643 | 44.8 | n/a    | 2   | 0.44 | 126 | 43.5 | n/a    | 2   | 0.06 |
| 117        | 114        | 160         | 26.7        | Prmtd.     | N/a      | n/a         | 0   | 15.7 | Prmtd. | N/a | n/a  | 0   | 7.8  | Prmtd. | N/a | n/a  |
| 117        | 120        | 585         | 9           | n/a        | n/a      | n/a         | 270 | 7.8  | n/a    | n/a | n/a  | 26  | 4.7  | n/a    | n/a | n/a  |
| 117        | 118        | 270         | 9           | n/a        | n/a      | n/a         | 135 | 7.8  | n/a    | n/a | n/a  | 27  | 4.7  | n/a    | n/a | n/a  |
| 119        | 116        | 287         | 31.2        | Prmtd.     | N/a      | n/a         | 216 | 22.3 | Prmtd. | N/a | n/a  | 62  | 14.8 | Prmtd. | N/a | n/a  |
| 119        | 114        | 463         | 14.7        | n/a        | n/a      | n/a         | 159 | 12   | n/a    | n/a | n/a  | 14  | 13.8 | n/a    | n/a | n/a  |
| 119        | 120        | 45          | 14.7        | n/a        | n/a      | n/a         | 23  | 12   | n/a    | n/a | n/a  | 5   | 13.8 | n/a    | n/a | n/a  |
| 121        | 126        | 105         | 64.6        | Prmtd.     | N/a      | n/a         | 53  | 27.9 | Prmtd. | N/a | n/a  | 15  | 15.5 | Prmtd. | N/a | n/a  |
| 121        | 124        | 991         | 12.7        | n/a        | n/a      | n/a         | 437 | 13.3 | n/a    | n/a | n/a  | 79  | 9.6  | n/a    | n/a | n/a  |
| 121        | 122        | 108         | 12.7        | n/a        | n/a      | n/a         | 154 | 13.3 | n/a    | n/a | n/a  | 32  | 9.6  | n/a    | n/a | n/a  |
| 122        | 87         | 618         | 44.7        | n/a        | 2        | 0.51        | 434 | 44.2 | n/a    | 2   | 0.34 | 75  | 43.4 | n/a    | 2   | 0.06 |
| 123        | 128        | 45          | 30.7        | Prmtd.     | N/a      | n/a         | 0   | 22.1 | Prmtd. | N/a | n/a  | 0   | 17.4 | Prmtd. | N/a | n/a  |
| 123        | 126        | 407         | 13          | n/a        | n/a      | n/a         | 158 | 11.8 | n/a    | n/a | n/a  | 44  | 10.8 | n/a    | n/a | n/a  |
| 123        | 124        | 148         | 13          | n/a        | n/a      | n/a         | 94  | 11.8 | n/a    | n/a | n/a  | 0   | 10.8 | n/a    | n/a | n/a  |
| 124        | 129        | 1364        | 31.3        | n/a        | 2        | 0.87        | 656 | 29.9 | n/a    | 2   | 0.46 | 118 | 29   | n/a    | 2   | 0.08 |
| 125        | 122        | 45          | 56.3        | Prmtd.     | N/a      | n/a         | 60  | 21.3 | Prmtd. | N/a | n/a  | 14  | 14   | Prmtd. | N/a | n/a  |
| 125        | 128        | 865         | 10.5        | n/a        | n/a      | n/a         | 353 | 9.3  | n/a    | n/a | n/a  | 42  | 8.4  | n/a    | n/a | n/a  |
| 125        | 126        | 313         | 10.5        | n/a        | n/a      | n/a         | 202 | 9.3  | n/a    | n/a | n/a  | 24  | 8.4  | n/a    | n/a | n/a  |
| 127        | 124        | 225         | 31.7        | Prmtd.     | N/a      | n/a         | 125 | 16.2 | Prmtd. | N/a | n/a  | 40  | 11.3 | Prmtd. | N/a | n/a  |

**Table B (Continued)**

|            |            |      |       |        |     |      |      |      |        |     |      |          |            |                |            |            |
|------------|------------|------|-------|--------|-----|------|------|------|--------|-----|------|----------|------------|----------------|------------|------------|
| 127        | 122        | 465  | 16.2  | n/a    | n/a | n/a  | 220  | 12.4 | n/a    | n/a | n/a  | 29       | 11.2       | n/a            | n/a        | n/a        |
| 127        | 128        | 105  | 16.2  | n/a    | n/a | n/a  | 53   | 12.4 | n/a    | n/a | n/a  | 11       | 11.2       | n/a            | n/a        | n/a        |
| 128        | 117        | 1015 | 45.8  | n/a    | 2   | 0.56 | 405  | 44.2 | n/a    | 2   | 0.31 | 53       | 43.3       | n/a            | 2          | 0.05       |
| 129        | 134        | 165  | 39.5  | Prmtd. | N/a | n/a  | 84   | 17.4 | Prmtd. | N/a | n/a  | 17       | 13         | Prmtd.         | N/a        | n/a        |
| 129        | 132        | 1156 | 9.6   | n/a    | n/a | n/a  | 572  | 9    | n/a    | n/a | n/a  | 102      | 8          | n/a            | n/a        | n/a        |
| 129        | 130        | 42   | 9.6   | n/a    | n/a | n/a  | 0    | 9    | n/a    | n/a | n/a  | 0        | 8          | n/a            | n/a        | n/a        |
| 130        | 95         | 543  | 44.5  | n/a    | 2   | 0.43 | 135  | 43.5 | n/a    | 2   | 0.21 | 21       | 43.2       | n/a            | 2          | 0.01       |
| <b>131</b> | <b>136</b> | 298  | 24.8  | Prmtd. | N/a | n/a  | 225  | 12.2 | Prmtd. | N/a | n/a  | <b>0</b> | <b>n/a</b> | <b>Prhted.</b> | <b>N/a</b> | <b>n/a</b> |
| 131        | 134        | 525  | 7.3   | n/a    | n/a | n/a  | 262  | 5.8  | n/a    | n/a | n/a  | 53       | 6.3        | n/a            | n/a        | n/a        |
| 131        | 132        | 223  | 7.3   | n/a    | n/a | n/a  | 154  | 5.8  | n/a    | n/a | n/a  | 99       | 6.3        | n/a            | n/a        | n/a        |
| 132        | 137        | 1770 | 64.3  | n/a    | 2   | 1.13 | 1011 | 61.1 | n/a    | 2   | 0.66 | 258      | 58.4       | n/a            | 2          | 0.13       |
| 133        | 130        | 0    | 168.1 | Prmtd. | N/a | n/a  | 0    | 40.4 | Prmtd. | N/a | n/a  | 0        | 23.1       | Prmtd.         | N/a        | n/a        |
| 133        | 136        | 720  | 18.6  | n/a    | n/a | n/a  | 263  | 15.2 | n/a    | n/a | n/a  | 48       | 13.6       | n/a            | n/a        | n/a        |
| 133        | 134        | 180  | 18.6  | n/a    | n/a | n/a  | 90   | 15.2 | n/a    | n/a | n/a  | 18       | 13.6       | n/a            | n/a        | n/a        |
| 135        | 132        | 390  | 39.9  | Prmtd. | N/a | n/a  | 285  | 23.6 | Prmtd. | N/a | n/a  | 57       | 11.8       | Prmtd.         | N/a        | n/a        |
| 135        | 130        | 500  | 15.5  | n/a    | n/a | n/a  | 135  | 12.3 | n/a    | n/a | n/a  | 21       | 11.7       | n/a            | n/a        | n/a        |
| 135        | 136        | 205  | 15.5  | n/a    | n/a | n/a  | 128  | 12.3 | n/a    | n/a | n/a  | 32       | 11.7       | n/a            | n/a        | n/a        |
| 136        | 125        | 1222 | 31    | n/a    | 2   | 0.86 | 615  | 29.8 | n/a    | 2   | 0.53 | 80       | 28.9       | n/a            | 2          | 0.09       |
| 137        | 142        | 328  | 43.6  | Prmtd. | N/a | n/a  | 188  | 19.7 | Prmtd. | N/a | n/a  | 54       | 12.9       | Prmtd.         | N/a        | n/a        |
| 137        | 140        | 1214 | 12.1  | n/a    | n/a | n/a  | 555  | 9.6  | n/a    | n/a | n/a  | 119      | 8          | n/a            | n/a        | n/a        |
| 137        | 138        | 227  | 12.1  | n/a    | n/a | n/a  | 269  | 9.6  | n/a    | n/a | n/a  | 85       | 8          | n/a            | n/a        | n/a        |
| 138        | 103        | 692  | 44.9  | n/a    | 2   | 0.56 | 599  | 44.7 | n/a    | 2   | 0.49 | 187      | 43.6       | n/a            | 2          | 0.16       |
| 139        | 144        | 60   | 28.6  | Prmtd. | N/a | n/a  | 0    | 22.3 | Prmtd. | N/a | n/a  | 0        | 17.6       | Prmtd.         | N/a        | n/a        |
| 139        | 142        | 437  | 12.1  | n/a    | n/a | n/a  | 195  | 11.9 | n/a    | n/a | n/a  | 23       | 10.8       | n/a            | n/a        | n/a        |
| 139        | 140        | 120  | 12.1  | n/a    | n/a | n/a  | 60   | 11.9 | n/a    | n/a | n/a  | 0        | 10.8       | n/a            | n/a        | n/a        |
| 140        | 145        | 1439 | 31.4  | n/a    | 2   | 0.86 | 668  | 29.9 | n/a    | 2   | 0.47 | 129      | 29         | n/a            | 2          | 0.11       |
| 141        | 138        | 0    | 128.1 | Prmtd. | N/a | n/a  | 98   | 20.3 | Prmtd. | N/a | n/a  | 56       | 9.1        | Prmtd.         | N/a        | n/a        |
| 141        | 144        | 600  | 10.8  | n/a    | n/a | n/a  | 233  | 7    | n/a    | n/a | n/a  | 42       | 8.9        | n/a            | n/a        | n/a        |
| 141        | 142        | 120  | 10.8  | n/a    | n/a | n/a  | 60   | 7    | n/a    | n/a | n/a  | 12       | 8.9        | n/a            | n/a        | n/a        |
| 143        | 140        | 105  | 21.9  | Prmtd. | N/a | n/a  | 53   | 12.2 | Prmtd. | N/a | n/a  | 11       | 11.5       | Prmtd.         | N/a        | n/a        |



**Table B (Continued)**

|     |     |     |      |        |     |      |     |      |        |     |      |     |      |        |     |      |
|-----|-----|-----|------|--------|-----|------|-----|------|--------|-----|------|-----|------|--------|-----|------|
| 143 | 138 | 465 | 15.8 | n/a    | n/a | n/a  | 233 | 13   | n/a    | n/a | n/a  | 47  | 11.6 | n/a    | n/a | n/a  |
| 143 | 144 | 240 | 15.8 | n/a    | n/a | n/a  | 120 | 13   | n/a    | n/a | n/a  | 24  | 11.6 | n/a    | n/a | n/a  |
| 144 | 133 | 900 | 60.6 | n/a    | 2   | 0.60 | 353 | 58.7 | n/a    | 2   | 0.45 | 66  | 57.8 | n/a    | 2   | 0.18 |
| 145 | 150 | 705 | 65.3 | Prmtd. | n/a | n/a  | 315 | 16.8 | Prmtd. | n/a | n/a  | 65  | 8.1  | Prmtd. | n/a | n/a  |
| 145 | 148 | 705 | 14.4 | n/a    | n/a | n/a  | 353 | 9.6  | n/a    | n/a | n/a  | 65  | 7.8  | n/a    | n/a | n/a  |
| 145 | 146 | 29  | 14.4 | n/a    | n/a | n/a  | 0   | 9.6  | n/a    | n/a | n/a  | 0   | 7.8  | n/a    | n/a | n/a  |
| 146 | 111 | 839 | 45.3 | n/a    | 2   | 0.53 | 375 | 44.1 | n/a    | 2   | 0.21 | 43  | 43.3 | n/a    | 2   | 0.02 |
| 147 | 152 | 0   | 29.4 | Prmtd. | n/a | n/a  | 0   | 22.4 | Prmtd. | n/a | n/a  | 0   | 18.1 | Prmtd. | n/a | n/a  |
| 147 | 150 | 180 | 12.1 | n/a    | n/a | n/a  | 128 | 11.8 | n/a    | n/a | n/a  | 24  | 11.3 | n/a    | n/a | n/a  |
| 147 | 148 | 195 | 12.1 | n/a    | n/a | n/a  | 98  | 11.8 | n/a    | n/a | n/a  | 26  | 11.3 | n/a    | n/a | n/a  |
| 149 | 146 | 315 | 52.3 | Prmtd. | n/a | n/a  | 128 | 19.4 | Prmtd. | n/a | n/a  | 22  | 11.5 | Prmtd. | n/a | n/a  |
| 149 | 152 | 450 | 15.1 | n/a    | n/a | n/a  | 255 | 12.3 | n/a    | n/a | n/a  | 54  | 11.6 | n/a    | n/a | n/a  |
| 149 | 150 | 60  | 15.1 | n/a    | n/a | n/a  | 30  | 12.3 | n/a    | n/a | n/a  | 6   | 11.6 | n/a    | n/a | n/a  |
| 151 | 148 | 75  | 14.2 | Prmtd. | n/a | n/a  | 38  | 11.6 | Prmtd. | n/a | n/a  | 8   | 11.5 | Prmtd. | n/a | n/a  |
| 151 | 146 | 495 | 14.8 | n/a    | n/a | n/a  | 248 | 12.8 | n/a    | n/a | n/a  | 21  | 11.7 | n/a    | n/a | n/a  |
| 151 | 152 | 270 | 14.8 | n/a    | n/a | n/a  | 135 | 12.8 | n/a    | n/a | n/a  | 56  | 11.7 | n/a    | n/a | n/a  |
| 152 | 141 | 720 | 30   | n/a    | 2   | 0.71 | 390 | 29.4 | n/a    | 2   | 0.30 | 110 | 29   | n/a    | 2   | 0.09 |

## REFERENCES

1. LeBlanc, L.J. "An Algorithm for the Discrete Network Design Problem." *Transportation Science* 9(3) (1975a): 183-199.
2. LeBlanc, L. J., Morlok, E. K., and Pierskalla, W. P. "An Efficient Approach to Solving the Road Network Equilibrium Traffic Assignment Problem." *Trans. Res.* 9 (1975b): 309-318.
3. Mouskos, K. C. *A Tabu-Based Heuristic Search Strategy to Solve a Discrete Transportation Equilibrium Network Design Problem*. 1991. Ph.D Thesis, The University of Texas at Austin.
4. LeBlanc, L. J. and Boyce, D. E. "A Bilevel Programming Algorithm for Exact Solution of the Network Design Problem with User-Optima Flows." *Transportation Research B*, vol. 20B, No.3 (1986): 259-265.
5. Sheffi, Y. *Urban Transportation Networks*. 1985. Prentice-Hall, Englewood Cliffs, New Jersey.
6. Abdulaal M., and LeBlanc, L. J. "Continuous Equilibrium Network Design Models." *Transportation Research B*, Vol. 13B (1979): 19-32.
7. Frank, M., and Wolfe, P. "An Algorithm for Quadratic Programming." *Naval Research Logistics Quarterly* 3(1-2) (1956): 95-110.
8. Friesz, T. L. "Transportation Network Equilibrium, Design and Aggregation: Key Developments and Research Opportunities." *Transportation Research A*, vol. 19A, No.5/6 (1985): 413-427.
9. Friesz, T. L., Cho, H. J., Mehta, N. J., Tobin R. L. and Anandalingam, G. "A simulated annealing approach to the Network Design Problem with Variational Inequality Constraints." *Transportation Science*, Vol. 26, No. 1(1992).
10. Wardrop, J. G. "Some Theoretical Aspects of Road Traffic Research." *Proc. Inst. Civ. Eng., 1, part II* (1952): 325-378.
11. Webster, F. V. "Traffic Signal Settings." *Road Research Technical Paper 39* (1958). Road Research Laboratory, Her Majesty's Stationary Office, London.
12. Beckerman, M. J., McGure, C. B., and Winston, C. B. *Studies in the Economics of Transportation*. 1956. Yale University Press, New Haven, Conn.

13. Berka, S., Boyce, D. E., Raj, J., Ran, B., Tarko, A., and Zhang, Y. "A large-scale route choice model with realistic link delay functions for generating highway travel times." *A technical report in support of the ADVANCE project to Illinois Department of Transportation*. 1994.
14. Magnanti, T. L. and Wong, R. T. "Network design and transportation planning: Models and Algorithms." *Transportation Science* 18 (4) (1984): 362-384.
15. Mahmassani, H. S. and Mouskos, K. C. "Some Numerical Results on the Diagonalization Algorithm for Network Assignment with Asymmetric Interactions Between Cars and Trucks." *Transportation Research* 22B (1988), 275-290.
16. Dionne, R. And Florian, M. "Exact and approximate algorithms for optimal network design." *Networks* 9 (1979): 37-60.
17. Fisk C. S. "Game Theory and Transportation Systems Modeling." *Transportation Research*, 18B (1984), 301-313.
18. Heydecker B. G. And Khoo T. K. "The Equilibrium Network Design Problem." *Proceedings of AIRO'90 Conference on Models and Methods for Decision Support*, Sorrento (1990), 587-602.
19. Hoang, H. H. "A Computational Approach to the Selection of an Optimal Network." *Management Science* 19 (1973): 488-498.
20. Marcotte P. "Network Optimization with Continuous Control Parameters." *Transportation Science* 17 (1983), 181-197.
21. Bard J. "An Efficient Point Algorithm for a Linear Two-stage Optimization Problem." *Operations Research*, 31 (1983): 670-684.
22. Bertsekas D. P. and Gafni E. M. "Projection Methods for Variational Inequalities with Application to the Traffic Assignment Problem." *Mathematical Programming Studies* 17(1982): 139-159.
23. Dafermos S. C. "Traffic Equilibria and Variational Inequality." *Transportation Science*, 14(1) (1980): 42-54.
24. Glover, F. "Future Paths for Integer Programming and Links to Artificial Intelligence." *Computers and Operations Research*, Vol. 13, No. 5 (1986): 533-549.
25. Glover, F. "Tabu Search-Part I." *ORSA J. Comput.* 1(1989): 190-206.
26. Glover, F. "Tabu Search-Part II." *ORSA J. Comput.* 2 (1990): 4-32.

27. Glover, F. and McMillan, C. "The general employee scheduling problem: An integration of MS and AI." *Comput. and Opns. Res.*, Vol. 13. No. 5 (1990): 533-549.
28. Jayakrishnan, R., Wei K. T., Prashker, J. N., and Rajadhyaksha, S. "Faster Path-Based Algorithm for Traffic Assignment." *Transportation Research Record 1443* (1992).
29. Kirkpatrick, S., Gelatt, C. D. and Vecchi, M. P. "Optimization by Simulated Annealing." *Science* 220 (1983): 671-680.
30. Matsuo, H., Suh, C. J., and Sullivan, R. S. "A Controlled Search Simulated Annealing Method for the Single Machine Weighted Tardiness Problem." *Working Paper 87-12-2*. 1987. Department of Management, University of Texas at Austin.
31. Meneguzzer, C., Boyce, D. E., Roupail, N., and Sen, A. *Implementation and Evaluation of an Asymmetric Equilibrium Route Choice Model Incorporating Intersection-Related Travel Times*, Report to Illinois Department of Transportation, Urban Transportation Center, University of Illinois, Chicago, Illinois, 1990.
32. Metropolis, N., Rosenbluth, A., Rosenbluth, M., Teller, A. and Teller, E. "Equation of state calculation by fast computing machines." *Journal of Chemical Physics* 21 (1953): 1087-1092.
33. Smith M. J. "Traffic Signals in Assignment." *Transportation Research*, 19B (1985), 155-160.
34. Allsop R. E. "Some Possibilities for Using Traffic Control to Influence Trip Destinations and Route Choice." *Proceedings of the Sixth International Symposium on transportation and Traffic Theory*, Sydney, Australia (1974), 345-374.
35. Cantarella G. E., Improta G. And Sforza A. "Iterative Procedure for Equilibrium Network Traffic Signal Setting." *Transportation Research*, 25A (1991), 241-249.
36. Chang, E. C. P., and Messer C. J. *PASSER II-90 Program User's Guide*. 1991. Texas Transportation Institute, Texas A&M University System, College Station, Texas 77843.
37. Dickson T. J. "A Note on Traffic Assignment and Signal Timings in A Signal Controlled Road Network." *Transportation Research*, 15B (1981), 267-271.
38. Garter N. H., Gershwin S. W., Little J. D. C. and Ross P. "Pilot Study of Computer-Based Urban Traffic Management." *Transportation Research*, 14 B (1980),

203-217.

39. *TRANSYT-7F User's Manual*. 1988. Transportation Research Center, University of Florida.
40. Yang, H. and Yagar S. "Traffic Assignment and Signal Control in Saturated Road Networks." *Transportation Research 29A* (1995), 125-139.
41. Ziliaskopoulos , A. K. And Mahmassani, H.S. 1996. "On Finding the Least Time Paths Considering Delays for Intersection Movements." *Transportation Research 30B* (1996), 359-367.
42. Rouphail, N.M., A. Tarko and C. Li "Signalized Intersections," Draft Chapter 9 of *Traffic Flow Theory Monograph*, January 1996.
43. Akcelik, R., "Traffic Signals: Capacity and Timing Analysis", *ARRB Research Report 123*, Australian Road Research Board, Victoria, Australia, March 1981.
44. Reilly, W., et al., "Capacity of Signalized Intersections," *Final Report, NCHRP Project 3-28(2)*, JHK&Associates, Tucson, AZ, 1983.
45. Roess, R., and McShane, W., "Final Report on the New Highway Capacity Manual," *Final Report, NCHRP Project 3-28(B)*, Transportation Training and Research Center, Polytechnic University, Brooklyn, NY, October 1986.
46. *Highway Capacity Manual, Special Report 209, 3<sup>rd</sup> edition*, Transportation Research Board, National Research Council, Washington, DC, 1997.
47. Little, J.D.C. "The Synchronization of Traffic Signals by Mixed-Integer Linear Programming", *Operation Research 14* (1966).
48. Marrus, B.S., and Main M.F. "New Method Improves Traffic Signal Timing", *Traffic Engineering*, 23-26 (1964).
49. "SIGOP: Traffic Signal Optimization Program-A Computer Program to Calculate Optimum Coordination in a Grid Network of Synchronized Traffic Signals," Traffic Research Corporation, New York, 1966.
50. Gartner, N.H., Little J.D.C., and Gabbay H., "Optimization of Traffic Signal Settings by Mixed-Integer Linear Programming. Part I: The Network Coordination Problem; Part II: The Network Synchronization Problem.", *Transportation Science 9* (1975).
51. Hillier, J.A., "Glasgow's Experiment in Area Traffic Control", *Traffic Engineering Control* (1965).

52. Greenshields, B., "A Study of Traffic Capacity," *Proceedings of the Highway Research Board*, Vol.14, Transportation Research Board, National Research Council, Washington, DC, 1934.
53. Dow, M., *CONMIN*, Australian National University, October, 1997.
54. Zeng, Q. A Combined Simulated Annealing and TABU Search Strategy to Solve Network Design Problem with Two Classes of Users, 1998. Ph.D Dissertation, Interdisciplinary Program in Transportation, New Jersey Institute of Technology, Newark, NJ.
55. Traffic Assignment Manual. Bureau of Public Roads, U. S. Department of Commerce, June 1964.
56. Skabardonis, A., and Dowling R. G., "Improved Speed-Flow Relationships for Planning Applications," *In Transportation Research Record 1572*, TRB, National Research Council, Washington, D.C., 1997.
57. Dowling R.G., Singh R., and Cheng W., "Accuracy and Performance of Improved Speed-Flow Curves," *In Transportation Research Record 1646*, TRB, National Research Council, Washington, D.C., 1998.