CHAPTER 1

INTRODUCTION

The growth of the number of automobiles on the roads has put a higher demand on the traffic control system to efficiently reduce the level of congestion occurrences, which increases travel delay, fuel consumption, and air pollution. Congestion is one of the most serious problems in highway traffic. The instability inherent in traffic flow due to the behavior of human drivers is one of the main causes of congestion. A long-standing problem in traffic engineering is to optimize the flow of vehicles through a given road network. Improving the timing of the traffic signals at intersections along arterials (or in a network) is generally considered as one of the most cost-effective means to reduce traffic congestion. However, because of the many complex aspects of a traffic system (e.g. vehicle flow interactions within the network, weather effects, traffic accidents, long-term and/or seasonal variations, etc.), it has been notoriously difficult to determine the optimal signal timing. This is especially the case on a system-wide (multiple intersections) basis [1, 2]. Much of this difficulty has stemmed from the need to build extremely complex traffic models as a component of the control strategy. Efficient traffic signal control has been recognized as an important component of the Advanced Traffic Management Systems of Intelligent Transportation Systems, currently pursued as a way for improving the efficiency of existing transportation facilities [3, 4].

The current computer controlled signal systems can be classified into two categories: fixed time control and traffic-responsive control. The fixed time control uses signal timing plans computed off-line using past data [e.g., 5, 6]. One of the quite popular methods is to use TRANSYT for signal timing optimization but the design is based on the average flows with the actual traffic fluctuations not taken into consideration. The traffic-responsive control computes the signal plans according to the prevailing traffic flow [7]. These control methods include, for example, the OPAC system (Optimized Policies for Adaptive Control) [8], SCOOT (Split, Cycle, and Offset Optimization Technique) [9, 10], SCAT system (Sydney Coordinated Adaptive Traffic System) [11], etc. The application of using neural networks (NNs) to traffic control has also been reported by many researchers (e.g., [12, 13]). These NN-based control strategies require a model for the traffic dynamics, which is usually constructed off-line using past system data. The model is usually a set of differential/difference equations, but it may also be a neural network or non-equation types of models such as fuzzy associative memory or rule-based expert system [14]. Whatever the type of model used, it is serving as a representation of the effect of the signal timings on the traffic flow in the network. It seems, however, that a trend to build more complex models is not going to produce sub-optimal control in realistic road networks with many intersections since there are numerous difficult-to-model interactions or other effects such as construction blockages, seasonal variations in flow patterns, etc. Therefore, it is desirable to develop effective traffic signal timing for an arterial or a road network without using traffic dynamic model. This is also true for small urban traffic flow study like traffic in downtown Duluth, and it is also the reason why we propose using a model-free approach to tackle the traffic signal timing issue due to sudden traffic surge over a short period of time after DECC special events.

Following special events at the DECC (e.g., conventions, concerts, graduation ceremonies, etc.), high volumes of traffic exiting the DECC create substantial congestion at adjacent intersections. The goal of this research is to provide an effective traffic signal timing control for the high volume traffic movements associated with DECC special events so that progression through the downtown Duluth and I-35 is as efficient as possible. Our research mainly focuses on the study of after event traffic flow data (over a 15 to 30-minute time period) at key intersections exit the DECC area and then develops an efficient traffic signal timing plan to reduce intersection delay and improve the overall traffic flow after events. The research contains the following four parts: (1) identify the project study area which includes adjacent and key intersections near the DECC. Only the signalized intersections having the most impact on the traffic flow exiting the DECC to I-35 and into downtown are considered; (2) collect, analyze, and research traffic data at the selected intersections; (3) develop an improved DECC event signal timing plan. A model-free approach using NNs with the weight estimation via the Simultaneous Perturbation Stochastic Approximation (SPSA) method is used [15]; and (4) perform evaluation study using the existing signal timing plan and the one developed by the SPSA algorithm. The results derived from the optimization algorithm are also compared with those generated using the Synchro software [16]. After consultation with the City of Duluth traffic signal engineer, our suggested split times (in percentage) following DECC special events are presented in this report. The timing plan developed here is based on the assumption that all signalized intersections are operated in coordinated mode, and the timing plan only applies to a short period of time (e.g., 30 minutes) immediately following special events. The time of duration depends on the size of events. The primary goal is to provide an improved coordinated signal timing plan at key intersections for the high volume traffic surge associated with DECC special events to reduce congestion. We believe that the signal timing plan developed in this report will greatly improve the sudden surge of events related traffic flow. It can help Mn/DOT District 1 and the City of Duluth Traffic Service Center manage the traffic flow following special events at the DECC more efficiently. In addition, with some minor modifications the results from this research can also be used to manage traffic flow for other scenarios (e.g., Grandma's Marathon, I-35 incident, etc.).

CHAPTER 2

THE PROJECT STUDY AREA

Based on field observations at the DECC after special events, we identified six key intersections which have more impact on the alleviation of traffic surge in our project study area. These intersections are:

- Superior Street/5th Avenue West
- I-35N/5th Avenue West
- I-35S/5th Avenue West
- I-35/Lake Avenue
- Railroad Street/Canal Park Drive
- Railroad Street/Lake Avenue

For easy reference, the area map showing the locations of the above intersections is given in Fig. 2.1.

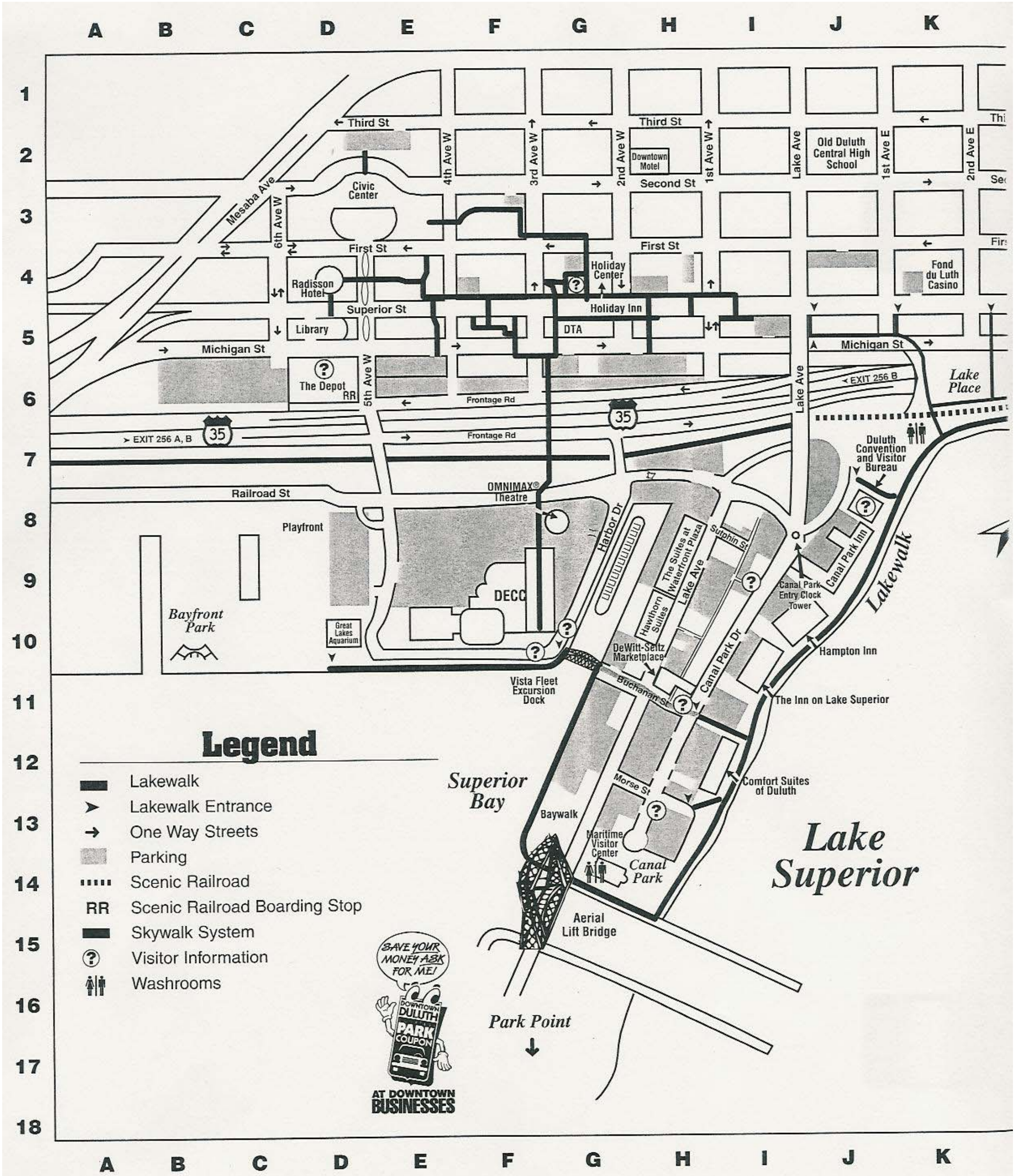


Fig. 2.1 The area map showing the intersections exit the DECC.

CHAPTER 3

SPECIAL EVENTS TRAFFIC DATA COLLECTION

The signal timing control algorithm for special events at the DECC, like any other demand-responsive controller, requires traffic data related to after-event traffic flow. Special events of our interest during the period of 2002-2003 included:

- Weekly activities (i.e., UMD Men's and Women's Hockey games, concerts)
- Annual events (i.e., Shrine Circus, UMD and College of St. Scholastic graduation ceremonies)

Based on the selected intersections within the project study area, the traffic data was collected using the traffic data counters/road tubes TT-2 and TT-4, which were borrowed from the City of Duluth Traffic Service Center. For detailed information about these data counters, please refer to the web site http://www.diamondtraffic.com. However, due to limited number of road tubes we can borrow and student helpers, we can only collect data at three intersections at a time. Therefore, we divided the area exit the DECC into two networks with each covering three adjacent intersections identified in Fig. 2.1. That is, the network 1, the 5th Avenue West section and the network 2, the Railroad Street section. The manual counts were also conducted mainly for the purpose of counting the turning movements at these intersections. Except graduation ceremonies, all the special events we studied were held on Fridays and Saturdays from 7 to 9 pm. The data was recorded over a short period of time, roughly 20 minutes, immediately after these events. Similar events data was further averaged and then converted to hourly traffic counts. Additional six video cameras were also used to collect data (images) for two special events (i.e., graduation ceremonies), which were held at 12 noon on May 10 and May 17, 2003. The traffic data counts were obtained from these video tapes through monitors and they were used to compare with those collected from the road tubes.

The special events data was collected from October 25, 2002 to May 17, 2003. Of the total 21 times over this period, 12 were for the UMD Men's and Women's Hockey games, 5 for the concerts and circus, and 4 for the graduation ceremonies. The dates when the data was collected are shown in the following Table 3.1.

(1) UMD Hockey

Intersection	Dates data collected
Superior Street/5th Avenue West	Oct. 25; Nov. 16; Dec. 6; Dec. 29 (2002); Feb. 7 (2003)
I-35N/5th Avenue West	Oct. 25; Nov. 16; Dec. 6; Dec. 29 (2002); Feb. 7 (2003)
I-35S/5th Avenue West	Oct. 25; Nov. 16; Dec. 6; Dec. 29 (2002); Feb. 7 (2003)
I-35/Lake Avenue	Oct. 26; Nov. 15; Nov. 22; Dec. 28 (2002);

	Feb. 8; March 7; March 8 (2003)
Railroad Street/Canal Park Drive	Oct. 26; Nov. 15; Nov. 22; Dec. 28 (2002); Feb. 8; March 7; March 8 (2003)
Railroad Street/Lake Avenue	Oct. 26; Nov. 15; Nov. 22; Dec. 28 (2002); Feb. 8; March 7; March 8 (2003)

(2) Concerts and Circus

Intersection	Dates data collected
Superior Street/5th Avenue West	Nov. 2 (2002); April 25 (2003)
I-35N/5th Avenue West	Nov. 2 (2002); April 25 (2003)
I-35S/5th Avenue West	Nov. 2 (2002); April 25 (2003)
I-35/Lake Avenue	Nov. 8; Dec. 31 (2002); April 26 (2003)
Railroad Street/Canal Park Drive	Nov. 8; Dec. 31 (2002); April 26 (2003)
Railroad Street/Lake Avenue	Nov. 8; Dec. 31 (2002); April 26 (2003)

(3) Commencements (UMD & College of St. Scholastic)

Intersection	Dates data collected
Superior Street/5th Avenue West	May 10; May 17 (2003)
I-35N/5th Avenue West	May 10; May 17 (2003)
I-35S/5th Avenue West	May 10; May 17 (2003)
I-35/Lake Avenue	May 10; May 17 (2003)
Railroad Street/Canal Park Drive	May 10; May 17 (2003)
Railroad Street/Lake Avenue	May 10; May 17 (2003)

Table 3.1 Dates of special events when the data was collected.

Figures 3.1-3.5 show the locations near the DECC where the data was collected. Note that these photos were taken before the scheduled DECC special events. The complete data together with some project related information can be found in our project web site http://www.d.umn.edu/~wwwmndot.

Fig. 3.1 Location at the intersection of Superior Street and 5th Avenue West (eastbound through traffic) where data was collected.

Fig. 3.2 Location at the intersection of Railroad Street and Lake Avenue (northbound right turn) where data was collected.

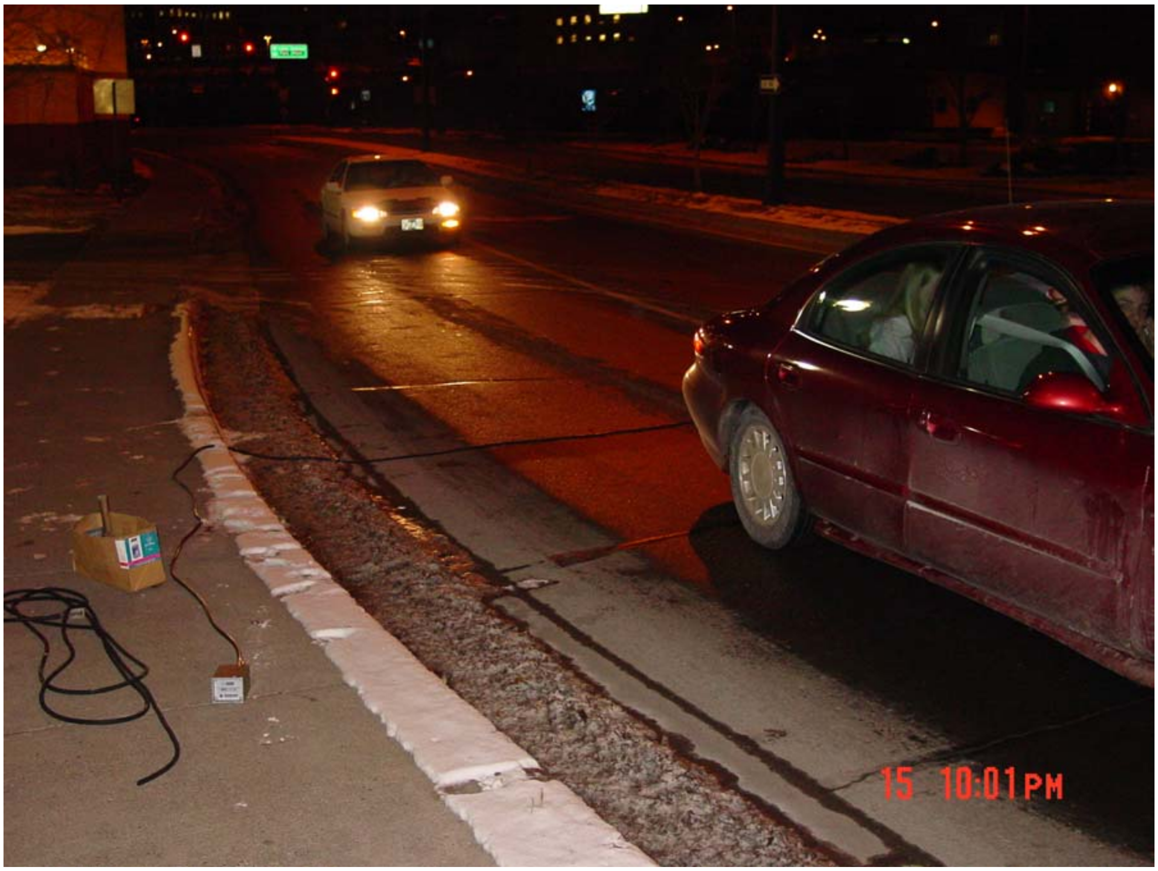


Fig. 3.3 Location near the intersection of Railroad Street and Canal Park Drive (eastbound right and through traffic) where data was collected.

Fig. 3.4 Location near the intersection of Railroad Street and Canal Park drive (northbound through traffic) where data was collected.

Fig. 3.5 Location at the intersection of Railroad Street and Lake Avenue (northbound right turn) where data was collected.

CHAPTER 4

THE SPSA ALGORITHM

Multivariate stochastic optimization plays a major role in the analysis and control of many engineering problems. In almost all real-world optimization problems, it is necessary to use a mathematical algorithm that iteratively seeks out the solution because an analytical (closed-form) solution is rarely available. Before reviewing the SPSA algorithm used in this research, we first provide some general background information on the stochastic optimization. The detail of the SPSA algorithm, the measure-of-effectiveness (MOE) criterion used, and its implementation are then followed.

BACKGROUND

The mathematical representation of most optimization problems is either the minimization or maximization of some scalar-valued objective function with respect to a vector of adjustable parameters. The optimization algorithm is a step-by-step procedure for changing the adjustable parameters from some initial guess (or set of guesses) to a value that offers an improvement in the objective function. Many optimization algorithms have been developed that assume a deterministic setting and that assume information is available on the gradient vector associated with the loss function. That is, the gradient of the loss function with respect to the parameters being optimized. However, there has been a growing interest in recursive optimization algorithms that do not depend on the direct gradient information or measurements (e.g., [15, 17, 18]). Rather, these algorithms are based on an approximation to the gradient formed from (generally noisy) measurements of the loss function. This interest has been motivated, for example, by problems in the adaptive control and statistical identification of complex systems, the optimization of processes by large Monte Carlo simulations, the training of recurrent neural networks, the recovery of images from noisy sensor data, and the design of complex queuing and discrete-event systems. Overall speaking, gradient-free stochastic algorithms exhibit convergence properties similar to the gradient-based stochastic algorithms (e.g., Robbins-Monro stochastic approximation (R-M SA) [19]) while requiring only loss function measurements. A main advantage of such algorithms is that they do not require the detailed knowledge of the functional relationship between the parameters being adjusted (optimized) and the loss function being optimized that is required in gradient-based algorithms. Such a relationship can be notoriously difficult to develop in some areas, whereas in other areas, there may be large computational savings in calculating a loss function relative to that required in calculating a gradient. For many real-world problems direct measurements of the gradient (with or without added noise) are not always obtainable. In contrast, the approaches based on gradient approximations require only conversion of the basic output measurements to sample values of the loss function, which does not require full knowledge of the system input-output relationships.

Unlike the signal timing study on the Miller Hill corridor which used a calibrated traffic flow model [20], this research took a fundamentally different approach that eliminates the need for traffic dynamic models. Our approach is based on NNs serving as the basis for the timing control with the weight estimation (i.e., the "training process") via the SPSA algorithm [15, 18]. The signal timing adjustments is designed to accommodate short-term traffic volume surge exiting the DECC following the special event. In other words, our implementation of signal timing optimization is based on the combination of two technologies: NN and SPSA algorithm. The NN serves to approximate the true (but unknown) mathematical function representing the optimal signal controller. This controller takes information from the traffic volumes and produces the signal timing to optimize the MOE. SPSA fulfills a role analogous to back propagation in providing values for the NN weights, but at the considerable advantage of not requiring a traffic model. As mentioned before, the main advantage of the SPSA algorithm is that it does not require direct gradient information to do optimization. The functional relationship between the parameters being adjusted (optimized) and the objective function (i.e., MOE) being minimized, together with its gradient, can be very difficult to derived in problem areas such as area-wide traffic control systems [21], complex queuing and discrete-event systems, etc. The great potential of using this algorithm with NN-related learning has been reported in [22]. Therefore, for this DECC special events signal timing study, we focused on researching and implementing the SPSA optimization technique using a practical model-free approach.

MOE CRITERION

The MOE used here is the total sum of the differences between the nominal throughput during the green phase and the average data (special events) we collected. The nominal throughput is a traffic count calculated from the speed limit (in vehicles per second) on the road segment times the green phase during time within the unit time. The intent is to use the road capacity and the traffic volume on the road in conjunction with the signal setting to minimize the traffic interruption caused by the traffic signal.

Within a unit time at a traffic signal, let v be speed limit in vehicles per second on the road sector facing the signal, t_g be the time of the green phase, l be the data collected, and T be the tolerance index for that signal. Then, $T = \rho\ (v\ t_g - l)$, where ρ is either 1 or 0 as it is either included or excluded from the computations. In our case, ρ is always set to be 1. That is, the value of the tolerance index is calculated from the difference between the nominal throughput and the actual data collected at each road segment within a unit time. The tolerance index would be the summation of the T's covering the whole period of interest (i.e., the short time period immediately after special events).

THE SPSA ALGORITHM

The SPSA algorithm is based on forming a succession of highly efficient approximations to the un-computable gradient of the loss function in the process of finding the optimal weights [15, 18, 23]. The approximation used in SPSA only requires observed values of the system (e.g., traffic queues) not a model for the system dynamics. Its procedure in the general recursive form is shown below:

$$\theta_{k+1} = \theta_k - a_k\, g_k(\theta_k)$$

where a_k is a scalar gain, $g_k(\theta_k)$ is the gradient estimate $\partial L/\partial\theta$ at $\theta = \theta_k$, and $L(\theta)$ is the MOE criterion (or the loss function). Note that the above equation simply states that the new estimate θ_{k+1} of θ equals to the previous estimate θ_k plus an adjustment that is proportional to the negative of the gradient estimate. Assume that the parameter vector θ (to be adjusted) is of dimension p, then the ith component of the gradient estimate $g_k(\theta_k)$ at $\theta = \theta_k$ is calculated as follows:

$$g_{ki}(\theta_k) = [Ł(\theta_k + c_k\Delta_k) - Ł(\theta_k - c_k\Delta_k)]/2\, c_k\Delta_{ki} \quad (i = 1, 2, \ldots, p)$$

where Ł(•) represents an observed value of L(•), $\Delta_k = (\Delta_{k1}, \Delta_{k2}, \ldots, \Delta_{kp})$ is a vector of random variables that satisfy certain important regularity conditions [15, 24], and c_k is a small positive number. Note that the numerators of $g_k(\theta)$ are identical; only the denominators are different. Therefore, to find $g_k(\theta)$, only two values of Ł(•) are needed. Starting with some initial weight vector θ_0, the step-by-step procedure for updating θ_k to θ_{k+1} is as follows:

1. Given the current weight vector estimate θ_k, change all values to $\theta_k + c_k\Delta_k$.

2. Throughout the given time period, use a NN control $u(\theta, \bullet)$ with weights $\theta = \theta_k + c_k\Delta_k$. Inputs to $u(\theta, \bullet)$ at any time within the period; include current state information.

3. Simulate the traffic flow via the *SimTraffic* software throughout the time period and form the loss function $Ł(\theta_k + c_k\Delta_k)$ based on the system behavior.

4. During the following same time period (i.e., the following date and time of the same DECC special event), repeat steps 1-3 with $\theta_k - c_k\Delta_k$ replacing $\theta_k + c_k\Delta_k$. Form $Ł(\theta_k - c_k\Delta_k)$.

5. With the information from steps 3 and 4 on $Ł(\theta_k + c_k\Delta_k)$ and $Ł(\theta_k - c_k\Delta_k)$, form the gradient estimate mentioned above, and then take one iteration of the SPSA algorithm to update the value of θ_k to θ_{k+1}.

6. Repeat steps 1-5 with the new θ_{k+1} replacing θ_k until traffic flow is optimized based on the chosen MOE.

The overall relationships between the NN controller, the SPSA algorithm, and traffic system is shown in Fig. 4.1.

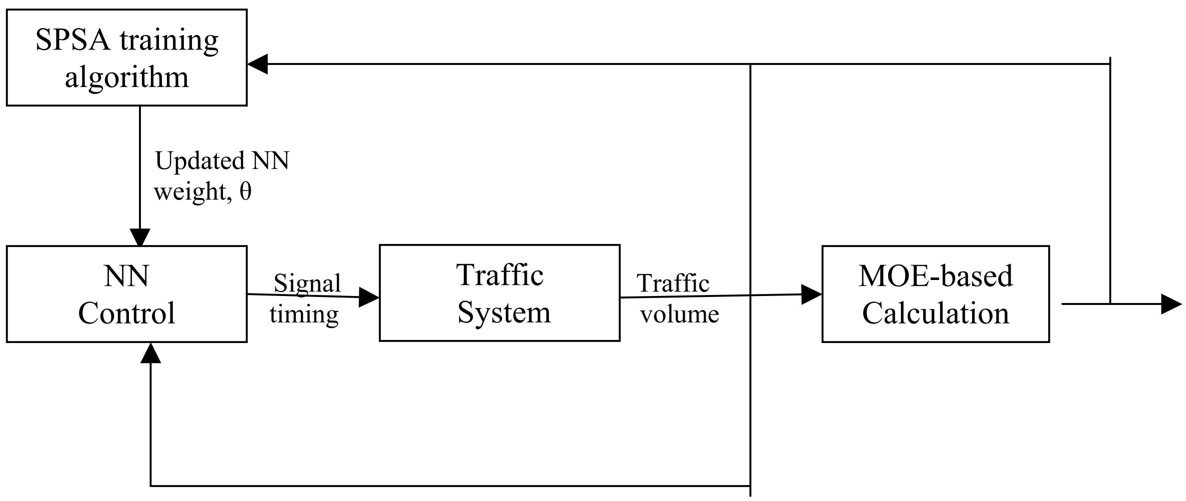


Fig. 4.1 Overall relationships between the NN control, the traffic system to be controlled, and the SPSA training process.

IMPLEMENTATION

The program implementing NN-based SPSA algorithm consists of three separate modules: the control module, the traffic flow simulation module, and the MOE evaluation module, all coded in Visual C++ 6.0. They are briefly described below.

1. Traffic Control Module

For the controller, we use a two-hidden-layer, feed-forward NN with 20 input nodes and 6 output nodes as shown in Fig. 4.2. The two hidden layers (i.e., layer 1 and layer 2) have 6 and 4 nodes, respectively. The 6 output nodes represent the green/red splits of the six intersections at the DECC. And the 20 input nodes are divided into two groups:

- The 14 outputs representing the averaged traffic volumes (vehicles per hour divided by cycles per hour) from external nodes to the networks
- The 6 outputs (vectors of timing splits) from the previous control solution.

2. *Simulation Module*

The simulation module takes the output timings from the NN controller to change the signal phases, moves traffic within the system, and counts the number of vehicles at the sensor locations.

3. MOE Module

This module computes the measure of effectiveness. It uses the averaged traffic volume and the corresponding signal timings to compute the traffic tolerance index every day. Although the simulation extends the time period to 24 hours every day, the output timing splits are used only to the 15 to 20-minutes period after DECC special events. Recall that the traffic tolerance index defined here is the total sum of the differences between the nominal throughput during the green phase and the average traffic volume.

The flow chart for the implementation of the NN-based SPSA algorithm is given in Fig. 4.3.

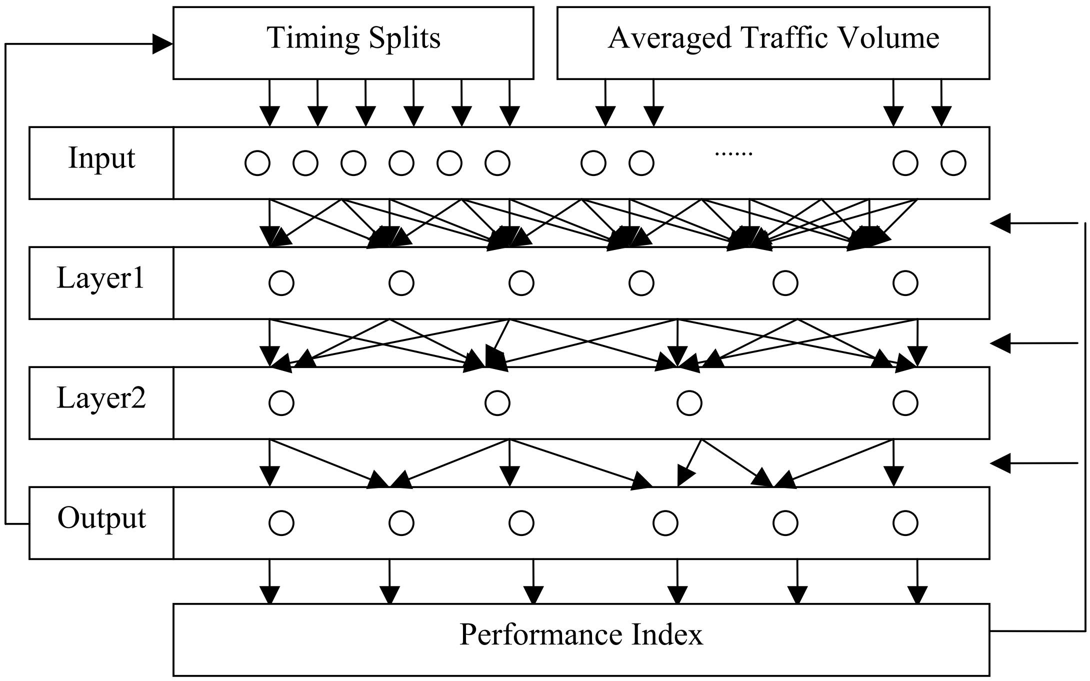


Fig. 4.2 The neural network controller’s internal structure.

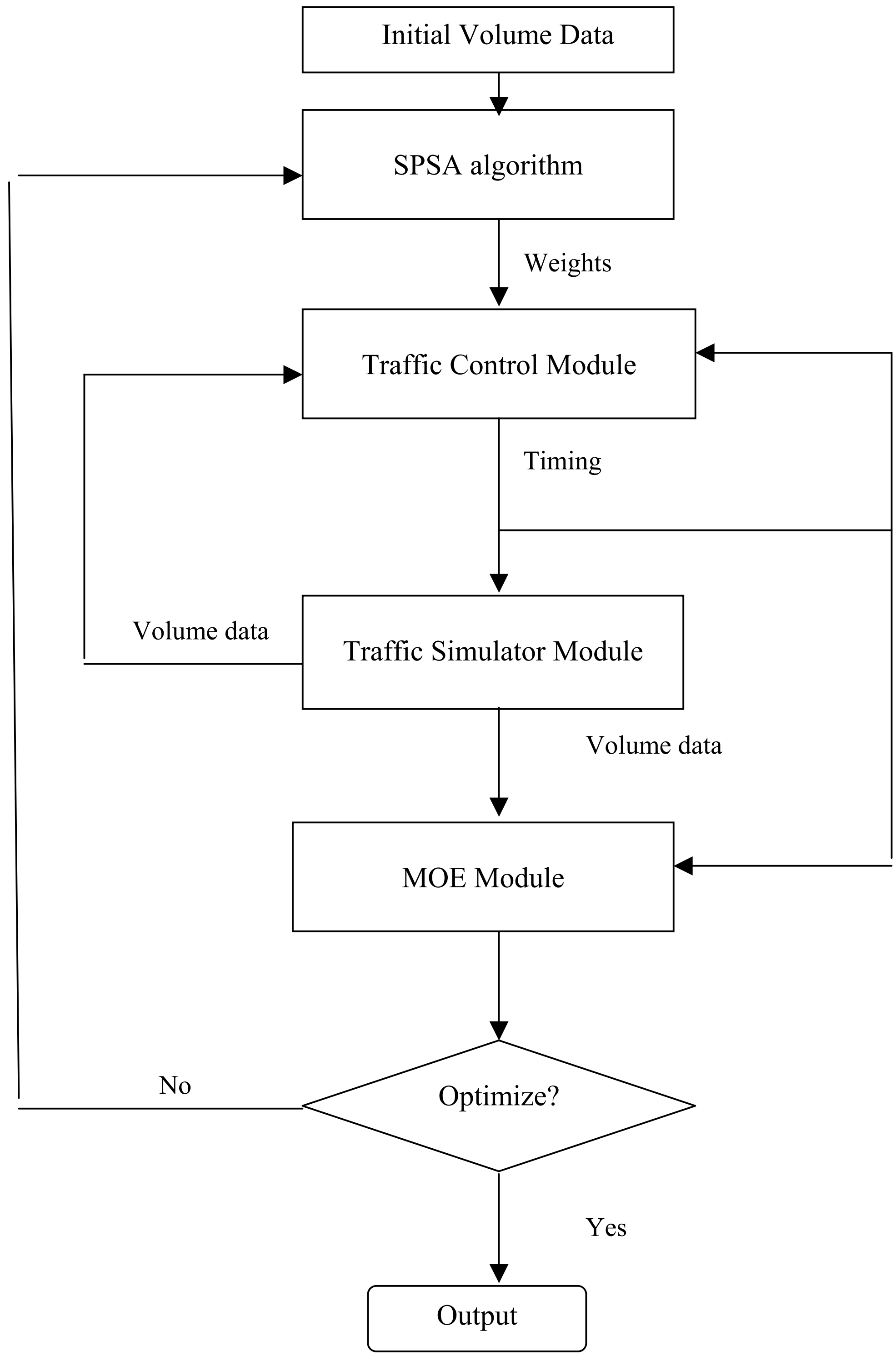


Fig. 4.3 Flow chart for the implementation of the NN based SPSA algorithm

CHAPTER 5

THE SIGNAL TIMING OPTIMIZATION

In this chapter, based on the SPSA algorithm we implemented in Chapter 4, a traffic signal timing plan that optimizes the split times at the six intersections near the DECC following the special events (i.e., UMD men's and women's hockey games) is developed. A computer software Synchro 5.0 is also used to aid in the signal optimization to compare the results generated by our SPSA algorithm. The Synchro 5.0 software is one of the most used signal timing optimization and traffic analysis software tools [16]. Please refer to the website http://www.trafficware.com for details. The recommended split times at the signalized intersections are suggested at the end of this chapter and this timing should help to ease the traffic flow following DECC special events. Note that the split times we suggested is based on the assumption that all six intersections are operating in coordinated mode. Currently, only one intersection at 5th Avenue West and Superior Street is in that mode, while the rest are operating in free mode.

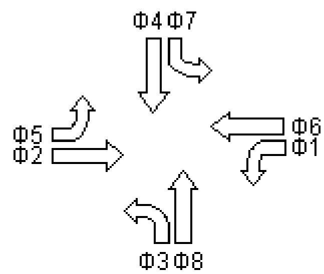
PRELIMINARIES

For clarity purpose, some of the most important terms used in this chapter are briefly explained as follows [25, 26]. The minimum initial (or minimum green) is the minimum initial green time for a phase or the shortest time that the phase can show green. The total lost time is the amount of time lost for a phase change. The minimum split is the shortest amount of time allowed for a phase. This minimum split must be long enough to accommodate the minimum initial interval plus yellow and all-red time. The total split is the current split time, and it is the amount of green, yellow, and all-red time assigned for each phase. Note that the all-red time should be of sufficient duration to permit the intersection to clear before cross traffic is released. The traffic timing at each intersection is broken apart into phases. A traffic signal phase (or split) is the part of the cycle given to an individual movement, or combination of non-conflicting movements during one or more intervals. An interval is a portion of the cycle during which the signal indications do not change. In general, there are eight possible phases at every intersection, although all of them are not always used. For example, there are three different phase plans used at the six intersections we studied. They are: six-phase (6Φ), five-phase (5Φ), and three-phase (3Φ) phase plans. The number of phases currently used at the intersections is shown in Table 5.1.

Intersection	Phase Plan
5th Avenue West & I-35 N	3 Φ
5th Avenue West & I-35 S	3 Φ
5th Avenue West & Superior Street	5 Φ
Railroad Street & Lake Avenue	5 Φ
Railroad Street & Canal Park Drive	6 Φ
Lake Avenue & I-35	6 Φ

Table 5.1 Number of phases used at the intersections near the DECC.

Phase numbers are the labels assigned to the individual movements around the intersection. It is common to assign the main street through movements as phase 2 (Φ2) and phase 6 (Φ6), and use odd numbers for left turn signals and even numbers for through signals (i.e., according to the National Electronics Manufacturing Association (NEMA) standards for signal controllers [25, 26]). A typical phase numbering scheme for an east/west arterial (e.g. Railroad Street) is like this: Φ2 (EBT, EBR), Φ5 (EBL), Φ6 (WBT, WBR), Φ1 (WBL), Φ4 (SBT, SBR), Φ7 (SBL), Φ3 (NBL), Φ8 (NBT, NBR), where EBT, EBR, EBL represent east bound through, east bound right, and east bound left, respectively (the same for the other directions). The figure below shows this phase numbering scheme for an east/west arterial, and the phase numbering scheme for a north/south arterial is similar except that all phase numbers should be rotated counterclockwise by 90 degrees.



East/West Main Street

Fig. 5.1 NEMA phases numbering convention for east/west arterial.

However, we found that none of the six intersections at the DECC follow the phase numbering convention mentioned above. A ring is a term used to describe a series of conflicting phases that occur in an established order. A ring may be a single ring, dual ring, or multi-ring. The traffic-actuated controller usually employs a dual ring concurrent timing process. The dual-ring controller uses a maximum of eight phase modules, each of which controls a single traffic movement with red, yellow, and green display. The eight phases are required to accommodate the eight movements (four through and four left turns) at the intersection. Phases 1 through 4 are included in ring 1, and phases 5 through 8 are included in ring 2. The two rings operate independently, except that their control must cross the “barrier” at the same time. The storage length is the length of a turning bay, and this data is used for analyzing potential blocking problems. Typically, the left turn type includes permitted, protected, permitted plus protected, etc.; while the right turn type has the options of permitted, protected, and free (i.e., free turn with acceleration lane), etc. The turning speed is the speed for vehicles while inside the intersection.

During this phase, we contacted Mars Cyr, the City of Duluth traffic signal engineer who is in charge of the signal timing, several times regarding the signal timing plans at the DECC. The cycle length used there during the weekdays is 80 seconds, except the time period from 3:30 pm to 7:00 am, where 100 seconds is used. The cycle length is the total time to complete one sequence of signalization around an intersection. Since we are focusing on rush hour traffic, the cycle length remains unchanged. In order to use the SPSA algorithm to develop a signal timing plan for the short time period immediately following special events, we first needed to gather information at all signalized intersections exit the DECC area. The data needed at each intersection includes lane configurations, road geometry, storage length for both right and left turn lanes, link distance, speed limit, turn type and turning speed, traffic volumes, minimum initial, total lost time, etc. Because the storage lanes information was not readily available, we measured these storage lengths for all the intersections. Furthermore, we manually measured turning speeds for right and left turns at each intersection. Depending on the road geometry inside the intersection (e.g., the acuteness of the turns), the turning speeds could be different; we found that they are roughly in the range of 7-15 mph. They averaged around 9 mph for a right turn and 12 mph for a left turn. The left turns along the corridor were also observed, and the proper types of turns (i.e., protected, protected-permissive, and permissive left turn) were recorded.

In addition, the traffic volumes for all possible directions at the intersections are needed. That is, besides the through traffic counts, the turning movement data is also needed. Therefore, manual counts were conducted over a 15- to 20-minute time period for both right and left turn lanes at these intersections and then converted to an hourly volume. We kept several data unchanged. These include: the minimum initial, all-red time, vehicle extension time, minimum gap time, walk and don't walk times (if any phase contains a pedestrian phase). The vehicle extension time is the amount of time by which the green time will be extended if a vehicle crosses the loop detector. In our case, the City installed one loop detector on 5th Avenue West close to the DECC west side parking lot, and another one was installed on Railroad Street next to Lake Avenue. The minimum gap time is the time the controller will use with volume-density operation. We set the total lost time to four seconds for all of the intersections we studied. The total lost time is a combination of the recognition time and all-red time. Recognition time is the time it takes an average driver to recognize the signal light has turned green, which is usually about two seconds.

SIGNAL TIMING

As mentioned before, the signal timing at five intersections is currently operating in "free" mode; only the timing at 5th Avenue West and Superior Street is in coordinated mode. In free mode, the green time allocated for each direction is not fixed. For example, initially a 14-second minimum green time is given in the north bound direction (i.e., Φ1) at the intersection of 5th Avenue West and I-35N. However, an additional green time (i.e., vehicle extension time) could be given to that direction traffic if the loop detectors sense vehicles back up. The vehicle extension time is the amount of time by which the green time will be extended if a vehicle crosses the loop detector. There are two loop detectors installed in the north bound two lanes on 5th Avenue West, about 300 feet south of the traffic signal lights at 5th Avenue and I-35N. Another two loop detectors are located near The William A. Irvin, about 350 feet from the signal lights at Railroad Street and Canal

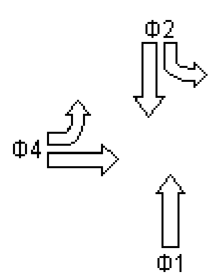
Park Drive. Although the intersections timing at I-35 & Lake Avenue and Railroad Street & Canal Park Drive can operate in coordinated mode, they are currently running in free mode by the City.

The timing plans generated by both the SPSA and Synchro computer programs are compared, studied, and re-adjusted. They are based on the assumption that all six intersections timings are operated in coordinated mode. Since the traffic pattern exit the DECC area is very similar following special events, the signal timing presented here can be applied to all DECC related events over a short period of time (e.g., 30 minutes). The time of duration depends on the size of the events. This timing plan was presented to Mars Cyr. After discussions, it was agreed that a 15% minimum should be placed on the total split times for each of the phases. For example, the split times of both the north and south bound (i.e., Φ4) at Superior Street and 5th Avenue West intersection was re-adjusted (the split time generated by SPSA was 13% due to low traffic volume recorded). When adjusting certain phases (usually left turn phase) to this minimum, adjustments had to be made so that the total split times for all the phases in an intersection did not exceed 100%. The results are summarized in Table 5.2.

Table 5.2 shows the original split times used by the City (if the coordinated mode is available), the optimized split times generated by both the SPSA and Synchro programs, and the suggested times after re-adjustments. In other words, the column labeled "Original (%)" represents the split times (in percentage of the cycle length) currently used by the city, the third and fourth columns represent the total split times generated by Synchro and SPSA, respectively; and the column labeled "Suggested (%)" represents the split times we suggested after our consultation with Mars Cyr. Note that there are three intersections with split times marked "----" under the column labeled "Original (%)" in Table 5.2, which simply means that the signal timing only operates in "free" mode (no coordinated mode available). For clarity, the corresponding phase numbering scheme used at each individual intersection is also given.

<u>Intersections</u>:

(1) 5th Avenue West and I-35 N

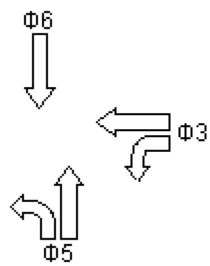


Ring 1: Φ1-Φ4/Ring 2: none

Φ1 – NBT & NBR
Φ2 - SBT & SBL
Φ4 - EBT & EBR & EBL

Phase	Original (%)	Synchro (%)	SPSA (%)	Suggested (%)
Φ1	----	60	54	55
Φ2	----	10	16	15
Φ4	----	30	30	30

(2) 5th Avenue West and I-35 S

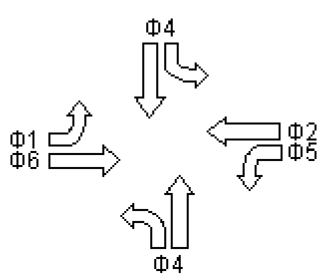


Ring 1: Φ3/Ring 2: Φ5, Φ6

Φ3 – WBT & WBR & WBL
Φ5 - NBT & NBL
Φ6 - SBT & SBR

Phase	Original (%)	Synchro (%)	SPSA (%)	Suggested (%)
Φ3	----	33.75	26	25
Φ5	----	18.75	49	50
Φ6	----	47.5	25	25

(3) 5th Avenue West and Superior Street

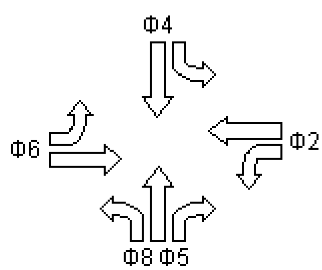


Ring 1: Φ1, Φ2, Φ4/Ring 2: Φ5, Φ6

Φ1 - EBL
Φ2 - WBT & WBR
Φ5 – WBL
Φ6 - EBT & EBR
Φ4 - NBT & NBR & NBL (yield on green) plus
SBT & SBR & SBL (yield on green)

Phase	Original (%)	Synchro (%)	SPSA (%)	Suggested (%)
Φ1	15	35	23	15
Φ2	45	35	64	50
Φ4	40	30	13	35
Φ5	15	35	23	15
Φ6	45	35	64	50

(4) Railroad Street and Lake Avenue

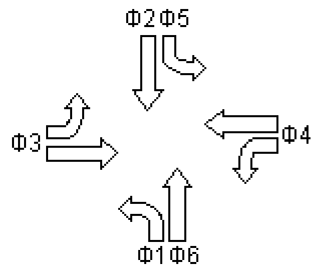


Ring 1: Φ2, Φ4/Ring 2: Φ5, Φ6, Φ8

Φ2 - WBT & WBR & WBL
Φ4 - SBT & SBR & SBL (yield on green)
Φ5 – NBR
Φ6 - EBT & EBR & EBL (yield on green)
Φ8 - NBT & NBL (yield on green)

Phase	Original (%)	Synchro (%)	SPSA (%)	Suggested (%)
Φ2	----	61.25	62	62
Φ4	----	28.75	19	19
Φ5	----	10	19	19
Φ6	-----	61.25	62	62
Φ8	-----	28.75	19	19

(5) Railroad Street and Canal Park Drive

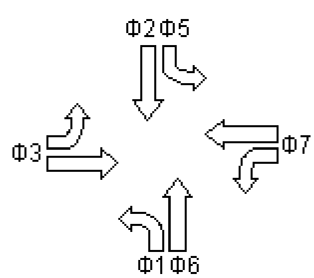


Ring 1: Φ1-Φ4/Ring 2: Φ5, Φ6

Φ1 – NBL
Φ2 - SBT & WBR
Φ3 - EBT & EBR & EBL
Φ4 - WBT & WBR & WBL
Φ5 – SBL
Φ6 – NBT & NBR

Phase	Original (%)	Synchro (%)	SPSA (%)	Suggested (%)
Φ1	15	10	16	15
Φ2	32	25	22	20
Φ3	33	45	43	45
Φ4	20	20	19	20
Φ5	15	10	16	15
Φ6	32	25	22	20

(6) Lake Avenue and I-35



Ring 1: Φ1-Φ3/Ring 2: Φ5-Φ7

Φ1 – NBL
Φ2 - SBT & SBR
Φ3 – EBT & EBR & EBL
Φ5 - SBL
Φ6 - NBT & EBR
Φ7 – WBT & WBR & WBL

Phase	Original (%)	Synchro (%)	SPSA (%)	Suggested (%)
Φ1	20	55.625	26	35
Φ2	50	18.75	55	45
Φ3	30	25.625	19	20
Φ5	20	55.625	26	35
Φ6	50	18.75	55	45
Φ7	30	25.625	19	20

Table 5.2 Comparison of total split times at the intersections near the DECC.

Note that all through traffic also allow right turn movements (in the same direction) unless specified. Phases at the intersections that occur at the same time are: (Φ1, Φ5), (Φ2, Φ6) – 5th Avenue West and Superior Street; (Φ2, Φ6), (Φ4, Φ8), (Φ5, Φ2) – Railroad Street and Lake Avenue; (Φ1, Φ5), (Φ2, Φ6) – Railroad Street and Canal Park Drive; (Φ1, Φ5), (Φ2, Φ6) (Φ3, Φ7) – Lake Avenue and I-35.

PERFORMANCE EVALUATION

The performance evaluation using the original timing plan and those generated by the Synchro software and the NN-based SPSA algorithm is studied. The evaluation is based on two MOE criteria; one is the tolerance index we used when using the SPSA algorithm, and the other is to measure the total delay per vehicle exit the DECC after special events. The comparison of the performance index in the network 1 (i.e., the traffic along 5th Avenue West section) and network 2 (i.e., the traffic along Railroad Street section) is given in Table 5.3 and Table 5.4, respectively. Table 5.5 shows the overall system performance with both networks combined together.

Since the tolerance index is used as our MOE, obviously, the SPSA algorithm generates the best results (i.e., the lowest value) in terms of that index measure (please refer to Tables 5.3 and 5.5), except for the network 2 where Synchro shows a better result. However, we found that Synchro produced an even worse result than the one currently used by the City for both the network 1 and the entire network.

The performance measure was also conducted based on the average total time delay incurred for each vehicle exit the network after events. In terms of this index measure (i.e., total delay per vehicle), it seemed that Synchro produced the best results. Since we only have the original timing splits for the intersections at Superior Street/5th Ave West, Railroad Street/Canal Park Drive and I-35/ Lake Avenue, the performance index we found by the original splits of these three intersections is 37.21, while the performance index by SPSA is 35.48. A 4.65% decrease in the performance measure shows the new traffic signal timing is superior to the current one used to alleviate the traffic surge following the DECC special events.

MOE	Original	Synchro	SPSA	Suggested
$\rho(vt_g - l)/l$	23.70	38.62	23.23	23.24
Delay/vehicle	47.10	48.40	53.70	43.70

Table 5.3 Comparison of the performance measures on 5th Avenue West.

MOE	Original	Synchro	SPSA	Suggested
$\rho(vt_g - l)/l$	26.54	22.55	25.28	25.31
Delay/vehicle	56.00	35.50	40.30	41.90

Table 5.4 Comparison of the performance measures on Railroad Street.

MOE	Original	Synchro	SPSA	Suggested
$\rho(vt_g - l)/l$	50.24	61.17	48.51	48.55
Delay/vehicle	103.10	83.90	94.00	85.60

Table 5.5 Comparison of the overall system performance measures.

Note that in Phase II of this research, we will focus on the critical issue of the mobility monitoring and performance. The basic question needs to be addressed is: how easy is it to exit the DECC area ? how much does that "ease of movement" vary after the DECC special events? That is, the mobility monitoring and performance measures between the travel conditions during the peak period (i.e., the time period immediately following special events) and off peak period (i.e., no-event daily flow situation) will be further investigated. A short-term travel time prediction using Kalman filtering technique will be further explored to monitor and gauge the quality of service of the routes exit the DECC area (i.e., Railroad Street, 5th Avenue West) following special events.

CHAPTER 6

CONCLUSION

Following special events at the DECC, high volumes of traffic exiting the DECC area create substantial congestion at adjacent intersections. The purpose of this research is to provide an effective signal timing control for the high volume traffic movements associated with DECC special events to reduce congestion. A practical approach for signal timing adjustments that eliminates the need of using traffic dynamic model is presented to optimize the signal timing following DECC special events. Our approach is based on neural networks with the weight estimation (i.e., the "training process") via the SPSA algorithm. Using the data collected, the NN-based control operates and makes signal timing adjustments to accommodate the traffic conditions. The NN weights are determined by use of the SPSA parallel estimation algorithm at the six intersections following special events. That is, we set up an SPSA estimation algorithm that allows for updating of the values of weights at each key intersection we studied. Therefore, there are two separate NNs, each with its own set of weights. The time period chosen is either 15-, 20- or 30-minute depending on the estimated size of the events/activities occurring at the DECC. Convergence was obtained when the MOE in terms of the tolerance index has been optimized subject to intersection capacity, minimum traffic light cycle length, etc. The results from SPSA algorithm are compared with those generated using the Synchro software. After consultation with the City of Duluth traffic signal engineer, our suggested split times (in percentage) following DECC special events are then presented in this report together with the related performance evaluation study. The main goal is to provide a more practical signal timing control, without using any traffic flow and system model, to address frequent occurrences of congestion and provide efficient traffic progression immediately following DECC events.

We believe that the timing plan suggested should help to move traffic exit the DECC area more efficiently. Furthermore, with some modifications the results from this study can also be used to manage traffic flow for other scenarios (e.g., Grandma's Marathon, I-35 incident, etc.). For example, during Grandma's Marathon, I-35 is closed between Mesaba Avenue and 26th Avenue East and the traffic is diverted to Mesaba Avenue, the one-way pair of 2nd Street and 3rd Street, and Superior Street. Similarly, if a major incident occurs in or near the tunnel area of I-35, the traffic will need to be diverted from I-35 through the downtown Duluth. That is, the timing plans will help manage diversion of traffic from I-35 to Mesaba Avenue, the one-way pair of 2nd Street and 3rd Street, and London Road during an incident in the tunnel area of I-35. The only difference is that the incident signal timing plan will utilize London Road, whereas the Grandma's route will use Superior Street [27].

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