Standard Title Page - Report on Federally Funded Project

1. Report No. FHWA/VTRC 06-CR8	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Investigation of Schedules for Traffic Signal Timing Optimization		5. Report Date November 2005 6. Performing Organization Code
7. Author(s) Byungkyu (Brian) Park and Seli James Agbolosu-Amison		8. Performing Organization Report No.
9. Performing Organization and Address Virginia Transportation Research Council 530 Edgemont Road Charlottesville, VA 22903		10. Work Unit No. (TRAIS) 11. Contract or Grant No. 72283
12. Sponsoring Agencies' Name and Address Virginia Department of Transportation 1401 E. Broad Street Richmond, VA 23219	FHWA P.O. Box 10249 Richmond, VA 23240	13. Type of Report and Period Covered Final: October 2002 – November 2005 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

Traffic signal optimization is recognized as one of the most cost-effective ways to improve urban mobility; however the extent of the benefits realized could significantly depend on how often traffic signal re-optimization occurs. Using a case study from the Northern Virginia Smart Traffic Signal System (NVSTSS), this project sought to determine how often traffic signals need to be re-optimized to provide the greatest benefits.

This project developed a new traffic signal timing plan evaluation and optimization program by combining the Integrated SYNCHRO and Platoon Dispersion (ISAPD) model and the OptQuest optimization program. Based on 2001 (base scenario) and 2004 traffic data, five scenarios of re-optimization time intervals (i.e., 2 weeks, 4 weeks, 8 weeks, 16 weeks, and 1 year) were investigated.

Study results indicate that (1) determining time intervals for re-optimization in the NVSTSS is feasible; (2) among the various re-optimization time intervals investigated for the Route 50 case study network, the time interval of 1 year was the best for both midday and the PM peak; and (3) the annual net savings from implementing this 1-year re-optimization time interval could be as high as $107,340 and $254,436, respectively, given the assumptions used in the study

The report recommends (1) the annual re-optimization of the Route 50 corridor traffic signal system; (2) the NVSTSS implementation of the combined ISAPS and OptQuest program for measuring "regrets" of not maintaining the optimal timing plan; (3) the adoption by VDOT traffic engineers of the methodology developed in this study, which is based on the combined ISAPD and OptQuest program, for making decisions regarding traffic signal re-optimization; and (4) a future study to investigate the impact of traffic volume growth rates and changes in turning movements as a means of assisting with determinations about traffic signal timing plan re-optimization.

17 Key Words Traffic Signal Optimization, Benefit Cost Analysis, Traffic Simulation, Traffic Signal Re-optimization	18. Distribution Statement No restrictions. This document is available to the public through NTIS, Springfield, VA 22161.		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 24	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

FINAL CONTRACT REPORT

INVESTIGATION OF SCHEDULES FOR TRAFFIC SIGNAL TIMING OPTIMIZATION

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Virginia Transportation Research Council
(A Cooperative Organization Sponsored Jointly by
the Virginia Department of Transportation and
the University of Virginia)

Charlottesville, Virginia

November 2005
VTRC 06-CR8

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Each contract report is peer reviewed and accepted for publication by Research Council staff with expertise in related technical areas. The contractor performs final editing and proofreading of the report.

ABSTRACT

Traffic signal optimization is recognized as one of the most cost-effective ways to improve urban mobility; however the extent of the benefits realized could significantly depend on how often traffic signal re-optimization occurs. Using a case study from the Northern Virginia Smart Traffic Signal System (NVSTSS), this project sought to determine how often traffic signals need to be re-optimized to result in the greatest benefits.

This project developed a new traffic signal timing plan evaluation and optimization program by combining the Integrated SYNCHRO And Platoon Dispersion (ISAPD) model and OptQuest optimization program. Based on traffic data from 2001 (base scenario) and 2004, five scenarios of re-optimization time intervals (i.e., 2 weeks, 4 weeks, 8 weeks, 16 weeks, and 1 year) were investigated using the ISAPD model and OptQuest optimization program.

The study concluded the following:

- The ISAPD model, which enhanced the delay estimation method in SYNCHRO by adding a platoon dispersion model, was successfully developed and combined with the OptQuest optimization engine for both development and evaluation of the traffic signal timing plan.

- The successful deployment of the proposed methodology for determining the timing interval for traffic signal re-optimization demonstrated that determining time intervals for re-optimization in the Northern Virginia Smart Traffic Signal System (NVSTSS) is feasible.

- The study reinforced the importance of maintaining good quality archived traffic data for similar studies. This is because the findings of this study were somewhat limited due to the availability of archived traffic data.

- Among the various re-optimization time intervals investigated for the Route 50 case study network, the time interval of one year was best for both midday and PM peak.

The study found that annual net savings of implementing a 1-year re-optimization time interval for the midday and PM peak in the Route 50 corridor could be as high as $107,340 and $254,436, respectively, given the assumptions used in the study.

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INTRODUCTION

Since Webster (1956) developed the principle of traffic signal timing optimization, many researchers have focused on the development and enhancement of signal timing control and optimization practices. Several analytical computer-based programs have been developed to generate better signal timing plans, including TRANSYT-7F (Wallace et al., 1991), SYNCHRO (Trafficware 2001), PASSER-II (Messer et al., 1974), etc. In addition, actuated signal control ultimately became the standard over pretimed control for most traffic signal systems. With advances in computer programs and technologies, optimal signal timing plans can now be generated and implemented. However, optimal signal timing plans can become outdated as traffic demand increases or changes over time. Updating any traffic signal timing plan would involve extensive data collection, network coding in a signal optimization program, and signal optimization and implementation, all of which is a relatively expensive exercise.

Research to date has clearly demonstrated the benefits of traffic signal optimization. However, it has failed to address the key issue encountered by the local traffic engineer - that is, “when” to re-optimize signal timing plans such that the effort is most cost-effective. Unfortunately, there is no straightforward answer to this question. If signal timing plans are not regularly updated, unnecessary delays and congestion will result. On the other hand, if signal timing plans are re-optimized too often, significant performance improvement for the signalized intersections may not result. Hence, there is an urgent need among traffic engineers to know optimum schedules (time intervals) for re-optimizing traffic signals. This project aims to address this need.

PURPOSE AND SCOPE

The purpose of this project was to develop a methodology that can determine realistic and cost effective time intervals for traffic signal re-optimization and to demonstrate the proposed methodology through the use of a case study. The scope of the project was limited to existing traffic signal control systems and the case study was conducted using a signalized arterial network (i.e., Route 50) in Northern Virginia's Smart Traffic Signal Systems (NVSTSS).

METHODS

To achieve the purpose of the proposed study, the following tasks were completed.

Task 1: Literature Review

To provide a foundation for the project, a detailed literature review was performed. However, it was limited to studies related to methods for developing time intervals for traffic signal re-optimizations. Further, selected cost metrics related to traffic signal re-optimization used by practitioners around the country were documented. The literature was obtained from the Transportation Research Board publications, journals, papers, and websites with information related to the subject of this project.

Task 2: Proposed Methodology and Selection/Development of Analytical Tool

The proposed methodology determines the optimal time interval for traffic signal re-optimization by comparing the associated benefits and costs between base case and various re-optimization intervals over a period of time. Thus, the methodology required both evaluation and optimization of traffic signal timing plans corresponding to multiple volume files. These volume files are each hourly volume for days considered for analysis. Thus, there was a need to select/develop a signal timing optimization and an evaluation tool that can be easily automated for handling multiple volume files.

Task 3: Case Study Site Selection and Data Reduction

It was determined that the best way to demonstrate a proposed methodology for determining time intervals for re-optimizing traffic signals would be a case study. Thus, a case study site, Route 50 corridor in Northern Virginia, was selected and data required to run the selected/developed analytical tool (Task 2) were prepared.

Task 4: Implementation of the Methodology via Case Study

This task involved (1) the development of base case and traffic signal re-optimization time interval scenarios and (2) implementation of the selected/developed analytical tool to estimate benefits of re-optimizing the timing plan for each scenario. Then, based on the estimated cost (obtained from Task 1) and the benefits, a cost benefit analysis was conducted to determine the best time interval (i.e., optimal schedule) for traffic signal timing re-optimization.

RESULTS AND DISCUSSION

Task 1: Literature Review

Literature related to signal timing re-optimization that included benefits and costs of re-optimization as well as optimization schedule was reviewed. The results are summarized in this section.

Wagner (1980) estimated that 21-29 gallons of fuel could be saved for every dollar spent on signal timing optimization which resulted in a benefit cost ratio of 20. The National Signal Timing Optimization Program (1982) observed 15,470 vehicle-hours savings per intersection, while Euler et al. (1983) found that 2 million gallons of fuel could be saved in a year by traffic signal re-optimization. Even though these studies demonstrated the benefits of signal timing re-optimization, they did not address appropriate time intervals for re-optimizing traffic signals. That is, they did not recommend how often traffic signals should be re-optimized so as to provide the greatest benefit cost ratio.

Parsonson (1992) conducted a survey on traffic signal timing improvement practices that was presented in NCHRP report No. 172. The survey attempted to determine optimum time intervals for re-optimizing traffic signals. Survey respondents recommended re-optimizing traffic signals between 1 and 3 years. One of the limitations of this study was that the responses were based solely on subjective experiences rather than engineering analysis, however.

Swayampakala and Graham (2005) investigated the optimal time interval required for the traffic signal timing re-optimization plan that accounts for both the financial costs of re-optimization and the economic gains incurred from reduced vehicular delays. This study was conducted for 13 isolated intersections in Charlotte, NC. Turning movement counts for these intersections were either collected every 1, 2, or 3 years. Data for these intersections were analyzed for every six-month interval within a 5 to 7 year period. The study used $13.25 per hour for each vehicle-hour delay savings based on the 2003 Urban Mobility Report for the Charlotte area, and $600 per intersection for the cost of signal re-optimization based on the data from the Greensboro Department of Transportation in North Carolina. The study concluded that re-optimizing signals at intervals of 24 to 30 months would be optimal.

Sabra, Wang & Associates (2003) identified that the cost of re-optimizing traffic signal timing plans ranges between $500 and $1,000 per intersection, depending on the number of time-of-day plans. In addition, a nationwide report on signal re-optimization practices from the Federal Highway Administration website stated that the cost of re-optimizing traffic signals from data collections to implementation is in the range of $500 and $3,000 per intersection. These costs as well as value of time (from the updated Urban Mobility Report) were used for the benefit cost analysis portion of this project

Task 2: Proposed Methodology and Selection/Development of Analytical Tool

The proposed methodology determines the optimal time interval for traffic signal re-optimization by conducting benefit cost analyses for the re-optimization timing interval scenarios. Benefits of each scenario were calculated by subtracting the total delay occurring under the scenario from the total delay which would have occurred by maintaining the base case timing plan, while costs of each scenario were estimated on the basis of actual costs of re-optimizing the traffic signal timing plan. Thus, the methodology required both evaluation and optimization of traffic signal timing under varying traffic demand conditions. Several microscopic traffic simulation models and traffic signal optimization programs were initially considered for this project. Upon the consideration of the already developed calibrated and validated model for the case study site and the current signal timing optimization program used by the Northern Virginia Smart Traffic Signal System (NVSTSS), the project team decided to investigate VISSIM (2004) and SYNCHRO (Trafficware, 2001).

Based on a well-calibrated VISSIM network developed from a previous research project (Park and Schneeberger, 2003), significant efforts were made to match the vehicular delays obtained from the calibrated VISSIM model to those estimated from SYNCHRO for various traffic volume and signal timing conditions. This exercise confirmed that it was almost impossible to match measures between microscopic and macroscopic simulation models simply due to discrepancies in their modeling fidelity. Even though inevitable discrepancies existed, the directional changes in their vehicular delays were similar. In other words, a set of optimized timing plans with lower traffic volume showing a lower delay in SYNCHRO resulted in a lower delay from VISSIM when compared to the other set of optimized timing plans with a higher volume case. Given that the use of microscopic simulation models for optimizing and/or evaluating traffic signal timing plans for hundreds of days is not feasible, the project team decided to use a macroscopic model for analysis.

Upon further assessment of the suitability of SYNCHRO for this project, the research team found that it lacked the capability of automating inputs of multiple traffic volumes (i.e., batch of input files). Furthermore, the SYNCHRO program manual clearly states that it does not use the platoon dispersion model. Given the significant impact of platoons on the performance of closely-spaced intersections, it was decided that the optimization process would provide more accurate results with the inclusion of a platoon dispersion model. In addition, SYNCHRO's inability to run a batch file makes it less attractive for this project due to the time and effort that would have to be invested in the evaluation of multiple traffic volumes. As a result, the project team decided to develop an enhanced SYNCHRO model that can automate the evaluation of timing plans under various traffic volume conditions and consider the platoon dispersion model (Mingwey et al., 1999, Wallace et al., 1998). Integrating these two features resulted in the development of an Integrated SYNCHRO And Platoon Dispersion (ISAPD) model. It is noted that the ISAPD model only adopted the SYNCHRO evaluation (or simulation) feature. This is because the optimization feature used in SYNCHRO was not the best method. For example, a semi-exhaustive search method used in SYNCHRO's offsets optimization could occasionally result in non-optimal solutions. Thus, an external optimization module was sought.

Among the various optimization techniques including genetic algorithm and simulated anneal, the project team chose a commercially-available program called OptQuest, which was developed by OptTek Systems (Glover et al., 1992). Preliminary experiments showed that OptQuest works very well for a deterministic optimization case. OptQuest is a global optimization software tool that allows users to automatically search for optimal solutions to complex systems. It allows users to easily define the parameters to control (e.g., cycle length, offsets, and maximum splits) the objective function.

ISAPD Model Development and Verification

Just like the evaluation module in the SYNCHO program, the ISAPD model can evaluate the performance of a traffic signal control system for a given set of inputs including geometry, turning movement counts, and traffic signal timing setting. The platoon dispersion model is only applied to the movements along the coordinated approaches when an arterial network is considered. That is, control delays on cross street movements were estimated without considering the platoon dispersion model.

The ISAPD model was initially developed in an MS Excel program and all the steps used in the calculation of control delay were verified with those of SYNCHRO. Once it was determined that no discrepancies exist between the Excel program and SYNCHRO, the platoon dispersion model was added into the Excel program. Then, the steps used in the Excel program were coded into the computer program using C++.

In order to demonstrate the performance of the ISAPD model, a simple network was proposed. This network consisted of two signalized intersections operating under the actuated coordinated mode and it was then coded into both the ISAPD model and SYNCHRO program. The distance between two signalized intersections was about 2000 ft, while the link speeds of major street movement and the minor street movement were 45 mph and 35 mph respectively. Traffic conditions were moderate as volume to capacity ratios for the movements were between 0.5 and 0.7. In addition, a cycle length of 60 seconds obtained from SYNCHRO optimization was used.

During the performance evaluation of SYNCHRO program and ISAPD model developed for the simple network, the impact of varying offsets (i.e., from 0 to 60 seconds) was investigated. Figures 1 and 2 illustrate the performance of the ISAPD model and SYNCHRO program. It can be clearly seen that the delays from the ISAPD model somewhat differ from those of SYNCHRO. The discrepancies in part are due to the impact of the platoon dispersion model used in the ISAPD model. In general, it appears that both delays by offsets show similar patterns.

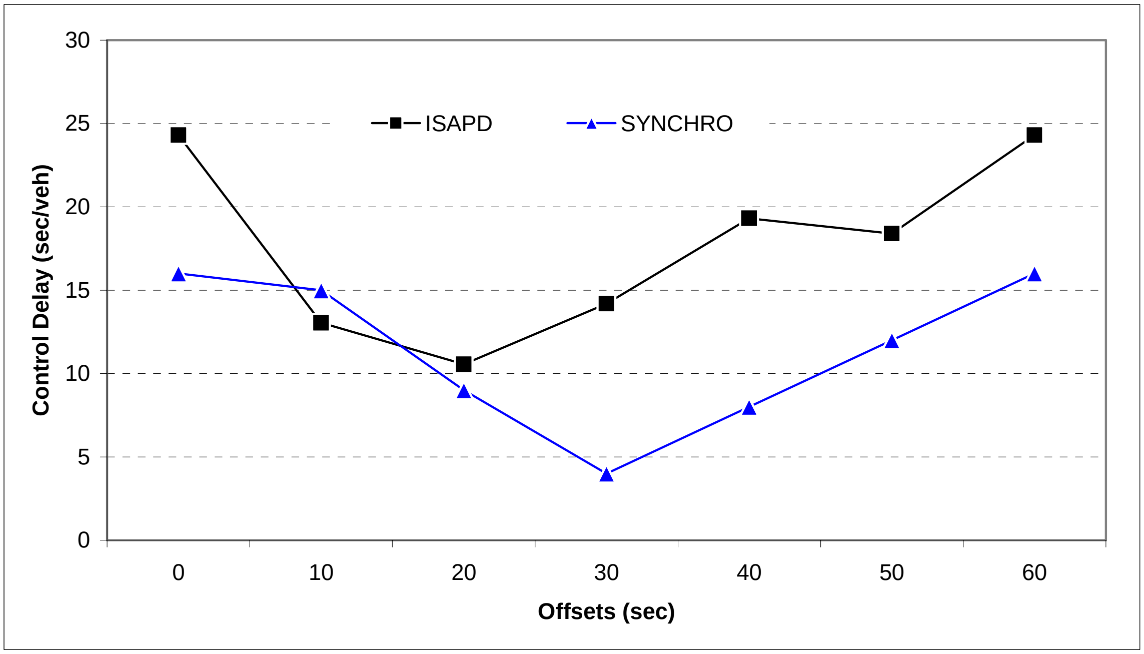

Figure 1. Comparison of ISAPD model and SYNCHRO program (EB direction)

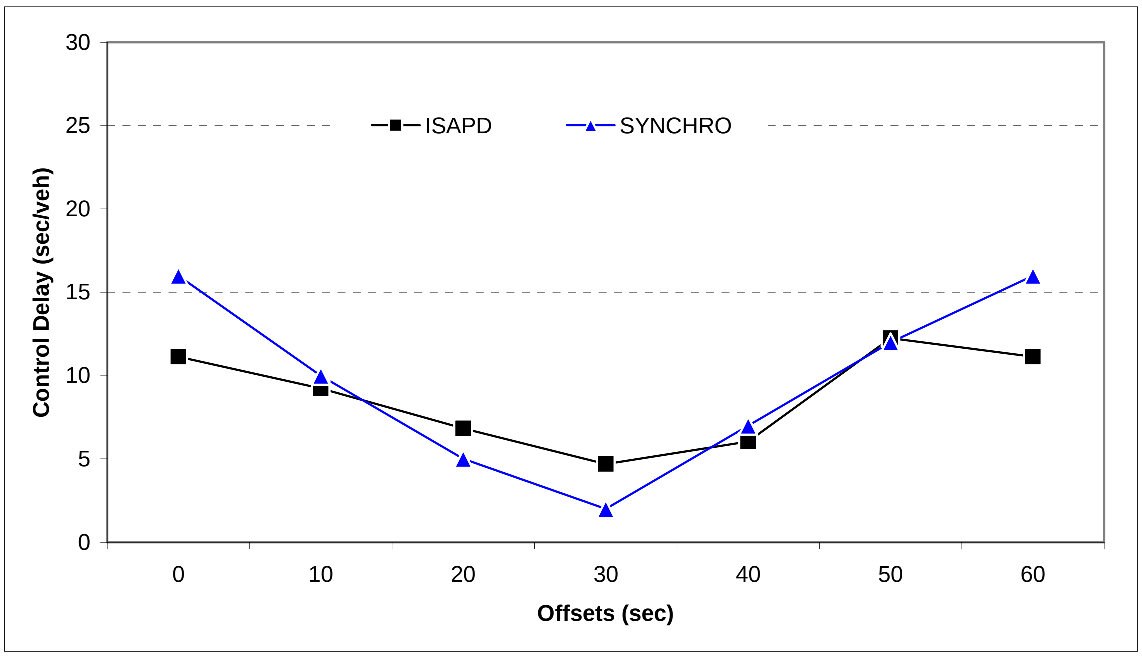

Figure 2. Comparison of ISAPD model and SYNCHRO program (WB direction)

OptQuest Program and Signal Timing Optimization

OptQuest, an optimization program, uses state-of-the-art meta-heuristic and mathematical optimization to guide the search for best solutions. In addition, the OptQuest engine provides an interface to other applications during optimization. Thus, the ISAPD model can be easily combined with the OptQuest program for traffic signal timing optimizations. For example, OptQuest starts from an initial solution of a traffic signal timing plan and the ISAPD evaluates the initial timing plan and provides the quality of its solution to OptQuest. Then OptQuest generates a new solution based on the quality of the previous solution. OptQuest finds the best solution quickly, as it uses state-of-the-art algorithms that are based on tabu-search, scatter search, integer programming, and neural networks, all of which can handle very complex optimization problems with ease. Thus, considering factors such as quality of solutions expected from the optimization, efficiency of the optimization tool, and the highly-acknowledged OptQuest software in operations research, OptQuest was chosen for this project (Glover, 1977, 1994 and 1996; Glover and Laguna, 1993).

The OptQuest program and the ISAPD model were integrated to optimize the traffic signal timing plan. As noted earlier, the ISAPD model and OptQuest program are evaluator and optimizer, respectively. The parameters optimized were cycle length, maximum splits and offsets. Figure 3 presents a traffic signal timing optimization process based on the combined ISAPD model and OptQuest program. The process starts with the ISAPD model taking inputs such as volume (turning movement counts) file and timing plan files (containing cycle length, maximum spits and offsets) with all other fixed inputs. It evaluates and produces an average system delay as an output to OptQuest. Then, OptQuest determines the next timing plan. These steps repeat until a predefined maximum number of iterations is reached. Among the optimized traffic signal timing plans, maximum splits for phases require special attention as they need to satisfy several constraints such as minimum requirement, barrier constraints, etc. Thus, a decoding scheme developed by Park et al. (1999) was adopted. The scheme decodes the parameters related to maximum splits to satisfy the constraints discussed earlier before being transferred to the ISAPD model.

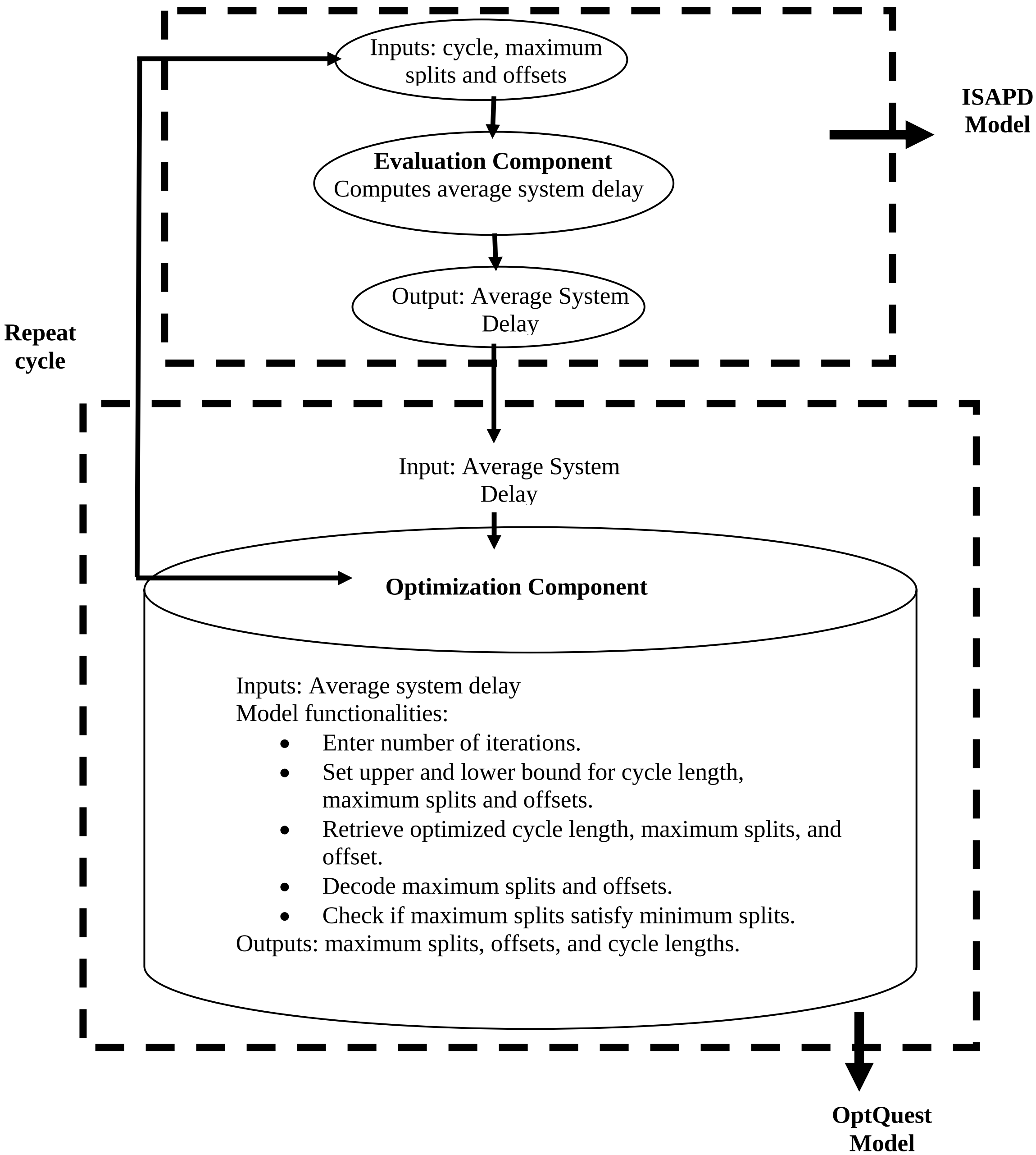

Figure 3. Signal Timing Optimization Process with ISAPD Model and OptQuest engine

Task 3: Case Study Site Selection and Data Reduction

Site Selection

An arterial network located on the Route 50 corridor in Northern Virginia was selected as the case study site. The site, known as Lee Jackson Memorial Highway, is composed of 11 signalized intersections between Rugby Road and Sullyfield Circle. This site was chosen because of the ease with which signal timing plans and detector data for these intersections could be extracted from the Management Information System for Transportation (MIST) workstation located in the Smart Travel Laboratory (STL) at the University of Virginia. This system is directly linked to the timing plans used in the field case study site and therefore provides access to real-time data. The schematic of this corridor is shown as a thick line in Figure 4 below. All of the signalized intersections on this corridor operate under the actuated signal coordination mode.

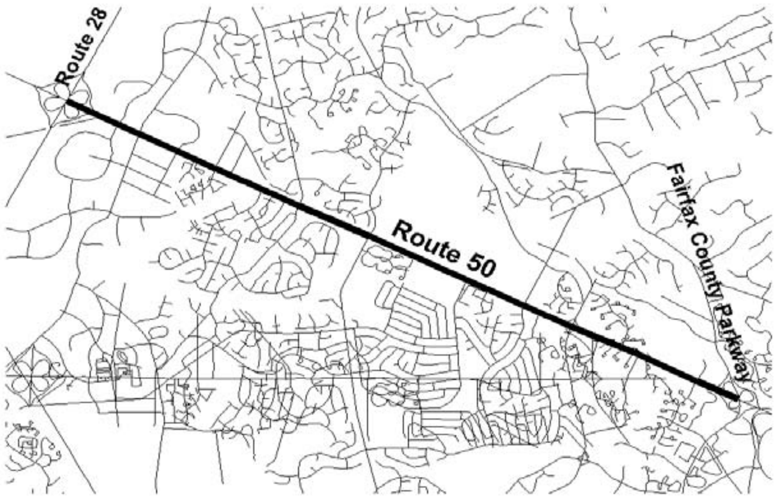

Figure 4. Test Site: A Segment of U.S. Route 50 Corridor
(Lee Jackson Memorial Highway, Fairfax, VA)

Data Reduction

Data were required for both network coding and scenario development and two sets of data were used in this study. One was VDOT's SYNCHRO files and the other was detector data (or turning movement counts) from the MIST system archived in the Smart Travel Laboratory at the University of Virginia.

VDOT's SYNCHRO files contain turning movement counts at the time of traffic signal timing optimization as well as network geometry and the existing signal timing plan. For the case study site, VDOT updated the traffic signal timing plan in April 2001. The ISAPD model was coded based on information obtained from SYNCHRO files. It is noted that this project only considered two time periods: midday (9 AM – 11 AM) and PM peak (4 PM – 6 PM). The turning movement counts were obtained from SYNCHRO files used for creating base case (i.e., 2001).

In addition to the data extracted from SYNCHRO files, both midday and PM peak detector data from January to September in 2004 were extracted from the MIST system. One reason that this case study used only 2004 data was due to data availability. The Smart Travel Laboratory (STL) began archiving both system and local detectors in 2004, which significantly enhanced the Northern Virginia Signal System Database by adding reasonably good quality of turning movement counts data. Before 2004, the STL only archived system detectors. Another reason for using only 2004 data was that detector data for 2002 and 2003 were not as good as that for 2004. In addition, for more than nine months during this period the STL received no detector data from NVSTSS MIST system due to problems with network connections.

Even though 2004 detector data quality was better than that for previous years, at times detector data were unrealistic or missing. Thus, detector data were "cleaned up" on the basis of screening algorithms developed by Turochy and Smith (2001). In addition to missing or bad detector data, some approaches did not have detectors. Given that the ISAPD model requires turning movement counts for every single movement, those missing detector data were estimated from adjacent intersections' turning movement counts assuming flow conservation holds. As a result, traffic volume files with each containing turning movement counts for all 11 intersections were generated. This resulted in the creation of 154 days of volume files for the PM peak and 159 days of volume files for midday. Each of the counts estimated was based on hourly volume.

Task 4: Implementation of the Methodology via Case Study

Scenario Development

As discussed, the proposed methodology evaluates the performance of various signal re-optimization time intervals and determines the optimal interval on the basis of benefit cost analysis. This involved scenario development for re-optimization time intervals and selection of representative volume to be used in signal optimization for each scenario.

In order to estimate the benefits of re-optimization for various time intervals, the base case is needed. The base was the traffic volume condition in 2001. It is noted that the timing plan actually implemented in 2001 was not used; instead a new timing plan was developed using the proposed ISAPD and OptQuest program. This was because the actually implemented timing plan (developed by SYNCHRO) in 2001 may not be optimal when evaluated in the ISAPD model. Thus, the base case consisted of 2001 volumes and an ISAPD-optimized timing plan. The next step was to develop scenarios for re-optimization intervals, and intervals of 2-week, 4-week, 8-week, 16-week, and 1 year were considered. Thus, a total of five scenarios of re-optimization time intervals were developed. To optimize a traffic signal timing plan for each interval, a corresponding volume needs to be prepared. For example, a scenario of a 2-week interval would require a representative volume for every two weeks. However, traffic engineers may not be able to obtain a representative volume for each interval of the scenarios. Thus, the researchers decided to use a median volume of the previous two weeks for developing an optimal timing plan. The median volume files were created by estimating median counts per turning movement from the previous 10 days' (since only weekdays were used) counts. As a result, 16 median volume files were created for each midday and PM peak.

ISAPD and OptQuest Program Optimization

The objective function used in the ISAPD and OptQuest program optimization was the average system delay while the total system delay was used as the performance measure for estimating benefits. Both of these measures are defined as follows:

The average system delay (ASD) is defined as:

$$ASD = \sum_{j}^{m} \left[\frac{\sum_{i}^{n} (TMC_{i,j} \times CD_{i,j})}{\sum_{i}^{n} TMC_{i,j}} \right] \qquad (1)$$

where:
ASD = average system delay in veh/sec
TMC_i = turning movement counts for the i-th movement
CDi = control delay for the i-th movement
i = number of movements, and
j = number of intersections.

Also total system delay (TSD) is defined as:

$$TSD = \sum_{j}^{m} \left[\sum_{i}^{n} (TMC_{i,j} \times CD_{i,j}) \right] \div 3600 \qquad (2)$$

where:
TSD = total system delay in vehicle-hours.

In order to ensure the timing plan developed from the ISAPD and OptQuest program is optimal, the convergence of the OptQuest search was investigated. The OptQuest program found good solutions in less than 2000 iterations. Thus, at each timing plan optimization run, 2000 iterations were made in the OptQuest search.

Evaluation Runs and Results

Both the midday and PM peak volume files developed for all weekdays, between January and September 2004, were analyzed to determine optimum time intervals for re-optimizing traffic signal timing plans. The evaluation started by developing optimal timing plans first which included timing plans for the base year 2001 as well as for every two weeks in 2004. For 2001, the volume file extracted from SYNCHRO file (developed in 2001) was used. For every 2-week interval scenario, the median volume files created for 2004 between January and September were used. In developing optimal timing plans for median volume files every two weeks, the initial point for the OptQuest search started from the optimal timing plan from the immediate 2-week scenario. This significantly enhanced the convergence of the OptQuest. The optimal timing plans for other scenarios were simply obtained from optimal timing plans of 2-week interval scenarios. Based on these six cases (i.e., base year 2001 and five scenarios based on time intervals), the performance was estimated by evaluating the optimal timing plans for each weekday for 2004. The evaluation process of the optimal timing plan for each scenario is explained. The entire process was done for both midday and PM peak periods.

For the base year, using the optimal timing plan for 2001 (base year), the total system delay was estimated for all weekdays between January and September, 2004.

For scenario 1, the optimal timing plan developed using the median volume file for the first 2 weeks (i.e., weeks 1 and 2) was used to evaluate volume files for the next two weeks (i.e., weeks 3 and 4). Next, the optimal timing plan for the median volume with the second two weeks (i.e., weeks 3 and 4) was used to evaluate volume files for the third two weeks (i.e., weeks 5 and 6). This was continued until the end of the dataset.

For scenario 2, the optimal timing plan developed using the median volume file for the first two weeks (i.e., weeks 1 and 2) was used to evaluate volume files for the next four weeks (weeks 3 through 6). Then, the optimal timing plan obtained from the median volume file for the previous two weeks (i.e., weeks 5 and 6) was used for the next four weeks (i.e., weeks 7 through 10), etc.

For scenario 3, the optimal timing plan developed using the median volume file for the first two weeks (i.e., weeks 1 and 2) was used to evaluate volume files for the next eight weeks (i.e., weeks 3 through 10). Then, the optimal timing plan obtained from the median volume file for the previous two weeks (i.e., weeks 9 and 10) was used for the next eight weeks (i.e., 11 through 18), etc.

For scenario 4, the optimal timing plan developed using the median volume file for the first two weeks (i.e., weeks 1 and 2) was used to evaluate volume files for the next 16 weeks (i.e., weeks 3 through 18). Then, the optimal timing plan obtained from the median volume file for the previous two weeks (i.e., weeks 17 and 18) was used for the next 16 weeks (i.e., 19 through 34), etc.

For scenario 5, the optimal timing plan developed using the median volume file for the first two weeks (i.e., weeks 1 and 2) was used to evaluate volume files for entire days in 2004.

In summary, for each scenario the optimal timing plans were used to evaluate volume files created for all weekdays between January and September 2004. The estimated total system delays are presented in Table 1. It is noted that total system delays were converted to annual delays. The percent reductions shown in Table 1 indicate the delay savings compared to the total delay incurred by maintaining the optimal traffic signal timing plan developed in 2001 for the entire year 2004 without re-optimizing it.

Table 1. Estimated Total System Delays and Delay Reductions for Midday and PM Peak in 2004

Case Number	Scenario Name	Midday		PM Peak	
		Total System Delays (TSD) (Veh-Hrs)	% Reduction in TSD (compared to Base year)	Total System Delays (TSD) (Veh-Hrs)	% Reduction in TSD (compared to Base year)
Base year	**Base year (2001)**	137,632.4	N/A	285,960.4	N/A
1	**2 weeks interval**	130,126.8	5.5	237,095.0	17.1
2	**4 weeks interval**	126,182.3	8.3	235,211.9	17.8
3	**8 weeks interval**	122,794.1	10.8	237,147.2	17.1
4	**16 weeks interval**	122,851.2	10.7	250,520.1	12.4
5	**1 year interval**	124,243.5	9.7	255,286.3	10.7

Table 1 clearly demonstrates that benefits can be expected from re-optimizing traffic signal timings. This result also supports the findings in the literature (Skabardonis, 2001, Euler et al., 1983, Wagner, 1980; National Signal Timing Optimization Program, 1982, Sabra, Wang & Associates, 2003).

For the midday period, the highest delay reduction was obtained for scenario 3 (i.e., 8 weeks interval) with TSD savings of 14,838 (137,632 – 122,794) vehicle-hours or delay reduction of over 10%. For PM peak, the highest delay saving was obtained for scenario 2 (i.e., 4 weeks interval) with TSD savings of 50,749 (285,960 – 235,211) vehicle-hours or delay reduction of almost 18%. Furthermore, the delay savings obtained are higher for the PM peak than the midday period for all cases. This makes sense as more vehicles are observed during the PM peak period than the midday period.

Benefit/Cost Analysis

Assumptions

Due to the unavailability of three years' worth of consecutive data, this project used only 2004 traffic volume data. Consequently, the project team had to make some assumptions in estimating delay savings of re-optimizing signal timing plans over three years. The following assumptions were made to interpolate delay savings that would have occurred between 2001 and 2004:

- The performance of the base year timing plan (i.e., optimized in year 2001) was degraded linearly over time. Thus, the trend of yearly delay savings between 2001 and 2004 were assumed to be linear.

- Total delay savings for the PM peak between scenarios 1 – 4 and base year in 2001 were assumed to be similar to total delay savings between scenarios 1 – 4 and scenario 5 in 2004. Thus, the delay savings of implementing scenarios 1 – 4 in 2001 under the base year timing plan are estimated from delay savings between scenarios 1 – 4 and scenario 5 (i.e., 1-year interval timing plan in 2004).

- Total delay savings for midday between scenarios 1 – 4 and the base year in 2001 were assumed to be negligible. The presence of little delay savings between scenarios 1 – 4 and scenario 5 (i.e., 1-year interval timing plan in 2004) for midday in 2004 support this assumption.

Estimation of Annual Delay Savings

The total delay savings of 13,389 vehicle hours were observed between the base year and 1-year scenario in 2004 for the midday time period (see Table 1). The savings were calculated by subtracting 124,243.5 (i.e., total delay under 1-year scenario) from 137,632.4 (i.e., total delay under base year). Assuming that no delay savings would have occurred in 2001, annual delay savings in 2002 and 2003 were interpolated on the basis of the linear relationship as shown in Figure 5.

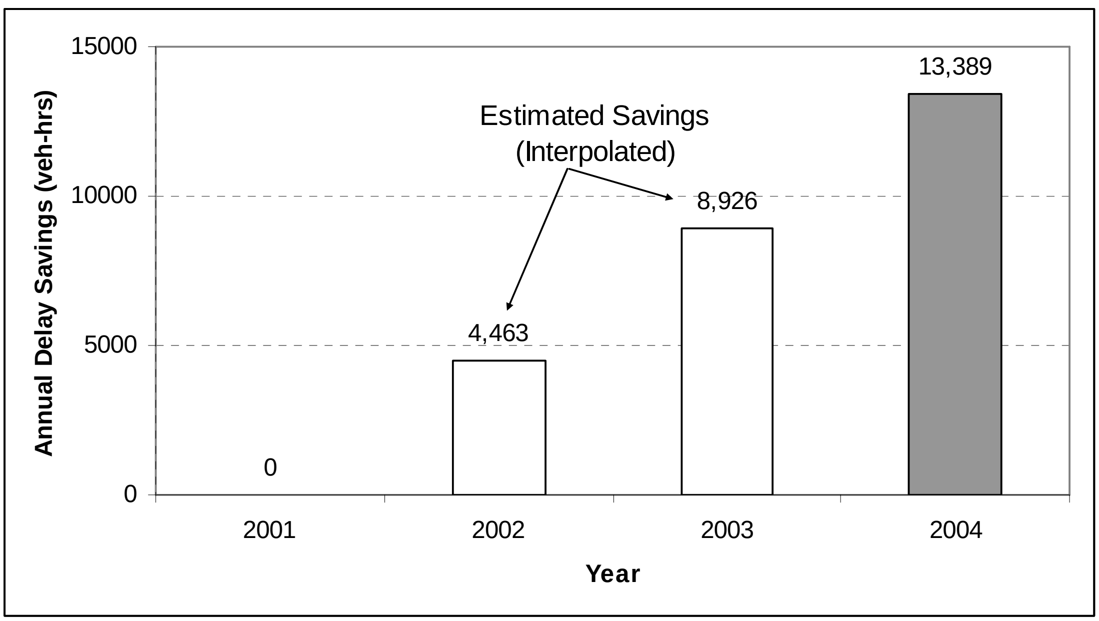

Figure 5. Estimated Delay Savings for Years 2002 and 2003 (Scenario 5, Midday)

Based on the above assumptions, delay savings in 2001 were obtained and delay savings in 2002 and 2003 were interpolated for every scenario. Then, total delay savings and annual delay savings were calculated and the results are presented in Table 2.

Table 2. Estimated Total and Annual Delay Savings between Base year and Scenarios

Period	Scenario Number	Scenario Name	Delay Savings by Year (veh-hr)				Total Delay Savings (veh-hr)	Annual Delay Savings (veh-hr)
			2001	2002	2003	2004		
Midday	1	2 wk	0	2,502	5,004	7,506	15,011	3,753
	2	4 wk	0	3,817	7,633	11,450	22,900	5,725
	3	8 wk	0	4,946	9,892	14,838	29,677	7,419
	4	16 wk	0	4,927	9,854	14,781	29,562	7,391
	5	1 year	0	4,463	8,926	13,389	26,778	6,694
PM Peak	1	2 wk	18,309	28,494	38,680	48,865	134,349	33,587
	2	4 wk	20,204	30,386	40,567	50,749	141,905	35,476
	3	8 wk	10,813	23,480	36,146	48,813	119,252	29,813
	4	16 wk	2,841	13,707	24,574	35,440	76,563	19,141
	5	1 year	0	10,225	20,449	30,674	61,348	15,337

Note: Delay savings of PM peak in 2001 were based on delay savings between scenarios 1-4 and scenario 5 in 2004. Delay savings in 2002 and 2003 were interpolated based on above assumptions.

Estimation of Annual Benefits and Cost

In order to determine the best time interval for traffic signal re-optimization, the annual delay savings obtained in Table 2 need to be converted to dollar savings and the cost of re-optimization needs to be estimated.

The metric used for calculating dollar savings was the average value (or cost) of time for the road user. A time value of $17.02 per hour of person travel was used for road users in the Northern Virginia area. This figure was obtained from the 2005 Urban Mobility Report (Schrank and Lomax, 2005). Multiplying this unit value with the savings in total system delays provided the amount of annual cost savings at the case study site when signal re-optimization is performed. For example, re-optimizing traffic signals for PM peak scenario 3 resulted in dollar savings of $507,419 ($17.02 × 29,813 vehicle-hours), while scenario 4 during midday saved $125,788 ($17.02 hour/vehicle × 7,391 vehicle-hours).

The next step was to estimate the total cost of traffic signal timing plan re-optimization. As discussed in the literature review results section, a recent FHWA study reported that the cost of traffic signal optimization ranges from $500 to $3,000 per intersection (Halkias, 2004). Given that the signalized intersections in the case study site maintain five time-of-day plans, it was assumed that the re-optimization cost per intersection was $3,000. Thus, the re-optimization cost per intersection for each time-of-day interval was $600, and the cost of re-optimizing 11 signalized intersections for each time-of-day interval was $6,600. This unit cost was multiplied by the number of times re-optimization was performed for each scenario with the exception of the base year. For example, scenario 1, which updated the traffic signal timing plan every two weeks, required 26 re-optimizations per year and the resulting total re-optimization costs are $171,600.

As can be seen from Table 3, for PM peak period, the costs of re-optimizing traffic signals are often significantly lower than the benefits in dollars. For example, scenario 4 at PM peak showed the benefits and costs were $325,774 and $21,450 respectively. For the midday period the costs of re-optimization exceeded the benefits for 2-week and 4-week interval scenarios, however.

Table 3. Estimated Annual Benefits and Cost by Scenarios

Period	Scenario Number	Scenario Name	Annual Delay Savings (veh-hr)	Benefits in $	Cost in $
Midday	1	2 wk	3,753	$63,873	$171,600
	2	4 wk	5,725	$97,440	$85,800
	3	8 wk	7,419	$126,274	$42,900
	4	16 wk	7,391	$125,788	$21,450
	5	1 year	6,694	$113,940	$6,600
PM Peak	1	2 wk	33,587	$571,654	$171,600
	2	4 wk	35,476	$603,806	$85,800
	3	8 wk	29,813	$507,419	$42,900
	4	16 wk	19,141	$325,774	$21,450
	5	1 year	15,337	$261,037	$6,600

To determine the best time interval for re-optimization of traffic signals, the benefit cost (b/c) ratio for each scenario was calculated. This ratio was obtained by simply dividing the benefits by the cost. Figure 6 presents the benefit cost ratios for the five scenarios considered. The b/c ratios of PM peak ranged from 3.3 to 39.6, while midday b/c ratios were between 0.4 and 17.3. This b/c ratio indicates that a 1-year interval of traffic signal timing re-optimization is the most appropriate among the scenarios considered.

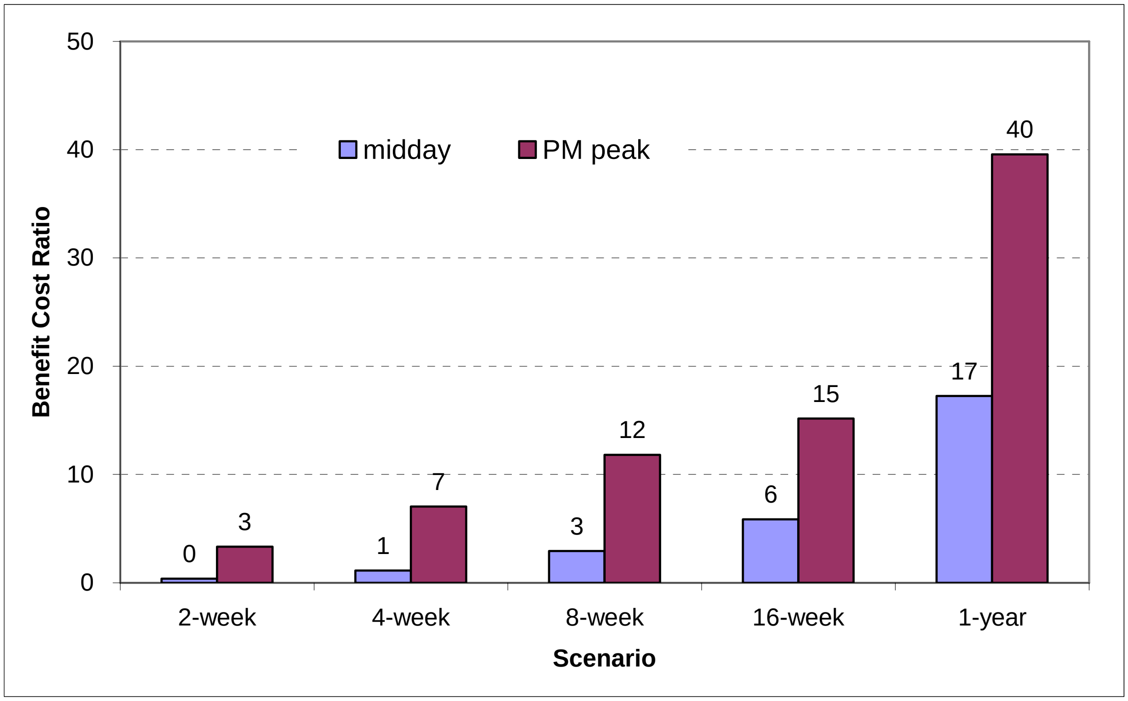

Figure 6. Benefit Cost Ratios by Scenarios

CONCLUSIONS

- The ISAPD model, which enhanced the delay estimation method in SYNCHRO by adding a platoon dispersion model, was successfully developed and combined with the OptQuest optimization engine for both development and evaluation of the traffic signal timing plan.

- The successful deployment of a new methodology for determining the timing interval for traffic signal re-optimization demonstrated for a case study conducted on the Route 50 corridor demonstrated that determining time intervals for re-optimization in the Northern Virginia Smart Traffic Signal System (NVSTSS) is feasible.

- The study reinforced the importance of maintaining good quality archived traffic data for similar studies. This is because the findings of this study were somewhat limited due to the availability of archived traffic data.

- Among the various re-optimization time intervals investigated for the Route 50 case study network, the time interval of one year was best for both midday and PM peak.

RECOMMENDATIONS

1. *Northern Virginia Smart Traffic Signal System (NVSTSS) traffic engineers should consider re-optimizing the Route 50 corridor traffic signal system annually.* The results of the case

study conducted in this project showed that a benefit cost ratio of 40 can be expected for PM peak by doing so.

2. *NVSTSS traffic engineers should consider implementing the combined ISAPD and OptQuest program for measuring "regrets (i.e., excess delay due to not implementing re-optimized timing plan)" of not maintaining the optimal timing plan.* The implementation of the combined ISAPD and OptQuest program can be achieved with minimal effort by doing the following:

   - The network coding for the ISAPD model can be done from the SYNCHRO input file. Note that Route 50 intersections were already coded for immediate use for NVSTSS. Other networks can be coded into the program with minimal effort.

   - Evaluate the performance (e.g., total system delay) of existing (i.e., field implemented) timing plan using current traffic volume data obtained from MIST system.

   - Optimize timing plan using the combined ISAPD and OptQuest program for the current traffic volume and obtain the performance (e.g., total system delay) under the optimized timing plan.

   - Calculate the "regrets" by subtracting total system delay for the existing timing plan from total system delay from the optimized timing plan.

3. *VDOT traffic engineers should consider adopting the proposed methodology based on the combined ISAPD and OptQuest program for making their business decisions on traffic signal re-optimization.* As clearly indicated by the results of this project, benefits can be gained by implementing the proposed methodology in other transportation districts in the Commonwealth.

4. *The proposed methodology based on the combined ISAPD and OptQuest program should be re-evaluated once at least three years worth of traffic volume data become available.* Because of data limitations, benefits for 2002 and 2003 had to be estimated. The assumption of linear timing plan degradation may not be accurate, so an additional evaluation that uses three years of actual data should be performed to determine whether the estimated benefits shown in this report are accurate.

5. *A future study should investigate the impact of traffic volume growth rates and changes in turning movement counts.* That future study should focus on generating guidelines that VDOT could use to determine traffic signal timing plan re-optimization schedules based on observed changes in traffic volumes.

BENEFITS AND COSTS ASSESSMENT

The project has demonstrated that re-optimizing traffic signal timing plans every year in the case study network (i.e., Route 50 corridor) could result in significant savings when compared to conducting it at the current 3-4 year interval. Based on the assumptions used in this analysis, the case study shows the net savings of using a 1-year re-optimization time interval for the midday and PM peak are $107,340 and $254,436 respectively. These net savings were calculated by subtracting costs from benefits. For example, the net saving for PM peak of $254,436 per intersection was calculated by subtracting the cost of re-optimization ($6,600) from total savings ($261,037). Further research should be conducted to see if similar net savings can be achieved for other corridors in the Commonwealth.

REFERENCES

Euler, G.W. and Wallace, C.E. Traffic Signal Optimization: Achieving National Objectives Through State and Local Government Actions. *ITE Journal,* September 1983, pp. 14-17.

Glover, F. Genetic algorithms and scatter search: unsuspected potentials. *Statistics and Computing* 1994, pp. 131-140.

Glover, F. Heuristics for integer programming using surrogate constraints. *Decision Sciences* 1977, pp. 156-166.

Glover, F. Tabu search and adaptive memory programming—advances, applications and challenges. *Interfaces in Computer Science and Operations Research,* eds. Barr, Helgason and Kennington, Kluwer Academic Publishers, 1997.

Glover, F., Kelly, J. P. and Laguna, M. Laguna OptTek Systems, Inc. in 1992. http://www.opttek.com/.

Glover, F. and M. Laguna. Tabu search. In *Modern Heuristic Techniques for Combinatorial Optimization*, ed. C. Reeves, 1993, 60-150. Blackwell Publishers: Oxford, UK.

Halkias, J. Traffic Signal Re-timing Program, Arterial Management under FHWA Operations Research Division, April 2004. http://www.ops.fhwa.dot.gov/aboutus/one_pagers/arterial_mgmt.pdf.

Holland, J. H. *Adaptation in Natural and Artificial Systems.* University of Michigan Press, Ann Arbor, MI. OptQuest for Crystal Ball User's Guide. Decisioneering Inc. Denver, CO, and Optimization Technologies, Inc., Boulder, CO, 1998.

Messer, C. J., H. E. Haenel, and E. A. Koeppe, *A Report on the User's Manual for Progression Analysis and Signal System Evaluation Routine – PASSER II*, TTI Research Report 165-14, College Station, Texas 1974.

Mingwey, W., and Jayakrishnan, R. *Network Traffic Signal Optimization Formulation with Embedded Platoon Dispersion Simulation* Transportation Research Record 1683, TRB, National Research Council, Washington, D.C., 1996, pp. 150–159.

National Signal Timing Optimization Project: Summary Evaluation Report. FHWA, U.S. Department of Transportation and University of Florida, Transportation Research Center, May 1982.

Park, B. Messer, C. J. Urbanik II, T. *Traffic Signal Optimization Program for Oversaturated Conditions Genetic Algorithm Approach.* In *Transportation Research Record 1683*, TRB, National Research Council, Washington, D.C., 1999, pp. 133–142.

Park, B. and Schneeberger, J.D. Microscopic Simulation Model Calibration and Validation: A Case Study of VISSIM for a Coordinated Actuated Signal System, *Transportation Research Record 1856*, TRB, National Research Council, Washington, D.C., 2003, pp. 185-192.

Parsonson, P. Signal Timing Improvement Practices. Synthesis of Highway Practice, No. 172, TRB, National Research Council, Washington, D.C., 1992, pp 1-10.

Robertson, D. I. *TRANSYT: A Traffic Network Study Tool.* Road Research Laboratory Report 253. Crowthorne, Berkshire, Great Britain, 1969.

Sabra, Wang & Associates, Signal timing process Final Report, for the FHWA operations division, Dec 2003.

Schrank, D. and Lomax, T. The 2005 Annual Urban Mobility Report. Texas Transportation Institute, Texas A&M University.

Skabardonis, A. ITS Benefits: The Case of traffic Signal Control Systems. Presented at 80th Annual Meeting of Transportation Research Board, Washington, D.C., 2001.

Swayampakala, R. K, Graham, J. R., *Optimal Timing Intervals for the Traffic Signal Re-Timing Process*, In 84th Annual TRB CD, 2004.

Trafficware Corporation. *SYNCHRO Users Guide*, 1009B Solano Ave, Albany CA, 94706. 1993 – 2001.

Turochy, R. E. and B. L. Smith, New Approach for Detector Data Screening in Traffic Management Systems, *Transportation Research Record 1727*, TRB, National Research Council, Washington, D.C., 2000, pp. 127-131.

VISSIM Version Manual, PTV Planug Transport Verkehr AG. Innovative Transportation Concepts, Inc., 2004.

Wagner, F. A. Energy Impacts of Urban Transportation Improvements. ITE journal, August 1980, pp 14 - 17.

Webster, F. V., *Traffic Signal Settings*, Road Research Technical Paper, No. 39, Her Majesty's Stationery Office, London, 1958.

Wallace, C. E., K. G. Courage, M. A. Hadi, and A. C. Gan, *TRANSYT-7F User's Guide*, Transportation Research Center, University of Florida, Gainesville, FL, March 1998.