NCHRP SYNTHESIS 409

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Traffic Signal Retiming Practices in the United States

Sponsored by the Federal Highway Administration

A Synthesis of Highway Practice

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

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Traffic Signal Retiming Practices in the United States

A Synthesis of Highway Practice

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SUBSCRIBER CATEGORIES
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TRANSPORTATION RESEARCH BOARD

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

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FOREWORD

Highway administrators, engineers, and researchers often face problems for which information already exists, either in documented form or as undocumented experience and practice. This information may be fragmented, scattered, and unevaluated. As a consequence, full knowledge of what has been learned about a problem may not be brought to bear on its solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem.

There is information on nearly every subject of concern to highway administrators and engineers. Much of it derives from research or from the work of practitioners faced with problems in their day-to-day work. To provide a systematic means for assembling and evaluating such useful information and to make it available to the entire highway community, the American Association of State Highway and Transportation Officials—through the mechanism of the National Cooperative Highway Research Program—authorized the Transportation Research Board to undertake a continuing study. This study, NCHRP Project 20-05, "Synthesis of Information Related to Highway Problems," searches out and synthesizes useful knowledge from all available sources and prepares concise, documented reports on specific topics. Reports from this endeavor constitute an NCHRP report series, *Synthesis of Highway Practice*.

This synthesis series reports on current knowledge and practice, in a compact format, without the detailed directions usually found in handbooks or design manuals. Each report in the series provides a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems.

PREFACE

By Gail R. Staba
Senior Program Officer
Transportation Research Board

This synthesis reports on the practices that operating agencies currently use to revise traffic signal timing. It includes the planning needed to develop signal timing plans and the processes used to develop, install, verify, fine-tune, and evaluate the plans. The author collected information for this synthesis through a literature review, a review of two large-scale and two narrowly focused surveys of transit agencies, and a series of project case studies. For the case studies, the author prepared an in-depth questionnaire to solicit detailed information not addressed in the prior survey. Of the 17 agencies solicited for the case studies, the author followed up with the 7 agencies that responded and were able to acquire additional statistical and anecdotal information.

Robert L. Gordon, Dunn Engineering Associates, Plainview, New York, collected and synthesized the information and wrote the report. The members of the topic panel are acknowledged on the preceding page. This synthesis is an immediately useful document that records the practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As progress in research and practice continues, new knowledge will be added to that now at hand.

CONTENTS

TRAFFIC SIGNAL RETIMING PRACTICES IN THE UNITED STATES

SUMMARY

Traffic signals that are not timed to coordinate efficiently with vehicular traffic can cause travel delays, increased accident rates, increased pollution from vehicle emissions, and increased fuel consumption, among other concerns. Although many studies have shown that retiming traffic signals is a cost-effective expenditure of transportation agency resources, few agencies have developed regular programs to carry out the retiming process. The *Urban Mobility Report* and *National Traffic Signal Report Card* publicize the need for and public benefit of traffic signal retiming: these reports indicate that almost half of the transportation agencies surveyed (43%) do not regularly collect and analyze traffic data for signal timing, and many existing traffic data collection programs do not assess the quality of data collected. As a result, even agencies that do make an effort to compile traffic signal information may be using faulty data to analyze and time their traffic signals.

Transportation agencies may need to explore new approaches to the signal retiming process in order to improve the quantity and quality of the traffic signal data collected and to streamline the use of new and existing resources. These new approaches may include cooperative action with other regional agencies, often with the assistance or leadership of a metropolitan planning organization. Interagency cooperation may allow transit agencies to assign more resources for signal timing or to improve the use of existing resources.

This synthesis reports on the practices that operating agencies currently use to revise traffic signal timing. It includes the planning needed to develop signal timing plans and the processes used to develop, install, verify, fine-tune, and evaluate the plans. The authors collected information for this synthesis through a literature review, a review of two large-scale and two narrowly focused surveys of transit agencies, and a series of project case studies. For the case studies, the authors prepared an in-depth questionnaire to solicit detailed information not addressed in the prior survey. Of the 17 agencies solicited for the case studies, the authors followed up with the 7 agencies that responded and were able to acquire additional statistical and anecdotal information.

The practices covered by this synthesis include the following:

- General signal control issues such as selecting intersections for coordination and determining different classes of intersection users. Agencies generally emphasize vehicle and pedestrian safety, as well as minimizing delay.
- Data collection requirements and intersection analysis, including phasing, retiming tools, coordination, and safety issues. Most agencies use standard retiming software to prepare timing plans, but the traffic movement data used in the software are usually collected manually, which decreases efficiency and increases the costs of the signal retiming process. Closed-circuit television is more frequently being used to assist in fine tuning, monitoring traffic, and determining timing needs, but other process improvements are required.
- Policy, management, and planning practices. Most agencies exceed the advised signal retiming interval of 30 to 36 months, largely because of limited resources. Agencies generally employ from three to seven daily timing plans, with two to three separate

timing plans for weekends, holidays, and special events. However, existing methodologies for identifying the number of timing plans needed and their periods of use are in need of improvement.

- Signal timing performance evaluation methods, such as travel time measurements, observations at intersections, crash records analysis, and public feedback. Most agencies track performance measures through delays, stops, route travel time, accident rates, and emissions and fuel consumption. Simulation and traffic detectors are used to a lesser extent for evaluation purposes. Transit agencies may be able to use emerging technologies to reduce the labor required to conduct field evaluations.
- Signal coordination across agency boundaries. Major barriers to signal coordination and shared control include technical barriers, and institutional legal and liability issues.

The literature and survey review and the case study evaluation produced several notable findings on the current state of traffic signal retiming. First, resource limitations are the most significant factor contributing to suboptimal signal retiming, even though many studies have shown signal timing to be a cost-effective expenditure of resources (with an average cost of $3,700 per signal and 26 person-hours of work for most agencies). Second, although current guidance states that traffic signals should be reviewed and retimed at intervals of 30 months to 3 years, most agencies exceed this interval but generally retime their signals within a 5-year period. Third, clearer and more detailed guidance is needed for several aspects of the signal retiming process, including coordination boundaries for traffic signal networks, interactions between controller timing plan parameters, and methods to establish the optimal number of timing plans to employ and the periods for use. Finally, further research to develop detailed design requirements for archived data user services and management systems for signal timing would reduce the cost of evaluating existing signal timing plans, and would also improve their usefulness in helping to determine the need for retiming.

CHAPTER ONE

INTRODUCTION AND RESEARCH METHODOLOGIES

PURPOSE OF SYNTHESIS

Traffic delays are widely reported to result in very large costs to the public in terms of traveler delay, excess fuel consumption, and excess emissions (Schrank and Lomax 2007). Many studies (e.g., Sunkari 2004; *Benefits of Retiming Traffic Signals* 2005) have shown that traffic signal retiming can significantly reduce these costs.

This synthesis presents current traffic signal retiming practices as provided in the literature and describes the results of in-depth case studies conducted by this project. It addresses the traffic signal retiming process in the context of traffic signal design, signal timing objectives, requirements, and practices. It also discusses strengths and weaknesses in the signal retiming process. Although the synthesis focuses on signal retiming, it also covers the larger issue of the relationship of signal timing to the management practices of agencies responsible for the signal timing process.

STUDY METHODOLOGY

The current practices described in the study were obtained from reviews of the literature, from several prior surveys, and from in-depth case studies conducted under this project.

The following documents are available to provide comprehensive guidance to traffic engineers on different aspects of signal timing practices:

- *Signal Timing on a Shoestring* (Henry 2005)
- *Traffic Control Devices Handbook 2001* (Pline 2001)
- *Traffic Signal Devices Handbook* (Bonneson et al. 2009)
- *Traffic Signal Timing Manual* (Koonce et al. 2008)

The synthesis also employed the following recent surveys:

- *National Traffic Signal Report Card* (National Transportation Operations Coalition 2007)

The National Transportation Operations Coalition (NTOC) is an organization comprising transportation experts including ITE, AASHTO, the American Public Works Association (APWA), the International Municipal Signal Association (IMSA), the Intelligent Transportation Society of America (ITS America), U.S.DOT–FHWA, and many other organizations. The results in the report card are based on the 2007 Traffic Signal Operation Self Assessment released by NTOC in the fall of 2006. A total of 417 agencies responded, representing 47 states. Each agency self-assessed progress in areas of traffic signal management, signal operations at individual intersections, signal operations in coordinated systems, signal timing practices, traffic monitoring and data collection, and traffic signal maintenance.

- *Puget Sound Regional ITS Implementation Plan* (Puget Sound Regional Council et al. 2008)

This report, sponsored by the Puget Sound Regional Council Traffic Operations Committee, provides leadership for regional traffic operations initiatives. It identifies ITS improvements for key multijurisdictional arterial corridors and works to provide capital to support better coordination among transportation agencies and create a more seamless transportation network. Data input for this plan includes a survey of 19 transportation agencies' practices regarding traffic management and signal timing.

- *Traffic Signal Operations and Maintenance Staffing Guidelines* (Gordon and Braud 2009)

This report provides guidelines to estimate the staffing and resource needs required to effectively operate and maintain traffic signal systems. The research effort included a literature review and in-depth survey responses from 7 agencies of 34, including cities, counties, and state DOTs.

- *Signal Timing Practices and Procedures* (Tarnoff and Ordonez 2004)

This manual, published and distributed by the FHWA and ITE, documents the state of practice in traffic signal timing. Results include the need for a comprehensive guide and are based on information obtained through a survey of more than 100 state, city, and county agencies responsible for traffic signal operations.

A set of in-depth case studies was conducted under this project. The case study agencies were selected for in-depth study because each represents a different experience, including a range of city sizes with a range of number of traffic signals, types, and operational practices. As such, the in-depth case studies are not intended to be representative of the population. Each case study was initiated with a detailed questionnaire so that their signal timing practices could be examined in depth. Appendix A provides the questionnaire, summarizes the responses, and describes the in-depth case study methodology. Agencies were selected for participation based on diverse geographical locations, and agency type and size. Of the 17 agencies solicited, 7 provided detailed responses to the questionnaire. Where responses appeared to have the potential for unique information, they were followed up with additional questions and discussion. In some cases agencies provided documentation that was directly incorporated into the synthesis. Table 1 identifies key characteristics of the in-depth case study participants.

The agencies contributing to the in-depth case studies are generally larger and have a greater level of resources than the average agency responding to the *National Traffic Signal Report Card* survey, resulting in generally better management practices.

ORGANIZATION OF SYNTHESIS

The results of the surveys and in-depth case studies are included in chapters two through eleven.

Chapter two discusses signal timing policy, management, and planning by responsible agencies, including objectives and policies.

Chapter three describes timing requirements and strategies at the network level. The chapter covers signal retiming issues such as network boundaries, retiming priorities, retiming frequency, the number of timing plans, and the periods for which they are employed.

Chapter four describes such retiming considerations as data collection, phasing, safety, detector placement, and signal retiming tools and simulation.

Chapter five covers the selection of actuated timing periods, relationships among phase intervals, pedestrian issues, and the frequency of signal retiming.

TABLE 1
KEY CHARACTERISTICS OF CASE STUDY RESPONDENTS

Designator	Type of Agency	Approximate Number of Signals	Location	Approximate Population	Signal System Type Employed: CL	C	A	TB	Resources Per Intersection Appropriate for Retiming[1]
a	County	500, 75% coordinated	Florida	1 million	√	√	√	√	16 eng hours, 40 tech hours, $5,000 if contracted
b	City	100, 97% coordinated	Illinois	150,000	√			√	3 eng hours, 14 tech hours, $2,500 if contracted
c	State DOT (geographical district)	700, 50% coordinated	Northeast	1.9 million	√				
d	County	700, 98% coordinated	Michigan	1.2 million		√	√	√	3 eng hours, 0.5 tech hour, $4,200 if contracted
e	City	150, 98% coordinated	New York	57,000		√		√	8 eng hours, 7 tech hours, $2,000 if contracted
f	City	850, 91% coordinated	Texas	660,000	√				$750 per intersection if contracted
g	State DOT (geographical district)	3,000, 75% coordinated	Midwest	Not applicable	√	√		√	$7,500 per intersection if contracted

CL = closed loop system , C = central control system, A = adaptive control system, TB = time base coordination, eng = engineer, tech = technician.
[1] The wide variation in contracting cost results, in part, from agencies contracting for some services and performing other services with their own forces. Figure 13 in chapter seven describes the apportionment of contracted costs among signal timing subtasks.

Chapter six discusses the installation of signal timing plans into field controllers, as well as verification and fine-tuning practices.

Chapter seven describes agency staffing levels. It also covers the person hours and dollar costs for various tasks associated with retiming as determined by the review of literature, the surveys, and in-depth case studies.

Chapter eight discusses performance measures described in the literature and those used by agencies.

Chapter nine presents practices for signal timing performance evaluation techniques used by agencies. It also describes emerging labor saving technology for obtaining such measures as delay. Other measures covered include safety, fuel consumption, emissions, and cost-benefit analysis.

Chapter ten provides practices from literature, the surveys, and in-depth case studies on barriers to implementation of signal timing plans, including resource limitations and institutional barriers such as signal coordination across agency boundaries and sharing of information devices. The limitations of available guidance and tools for signal timing as well as competing requirements are described.

Chapter eleven describes survey results, in-depth case studies, and literature reviews pertaining to methods to increase the resources for signal timing.

Chapter twelve provides conclusions and approaches for further research.

The survey and in-depth case study results are included in chapters two through eleven.

The references and a glossary are provided. Appendix A describes the in-depth case studies. Appendices B through E further discuss and provide examples of the material in the synthesis.

CHAPTER TWO

SIGNAL TIMING POLICY, MANAGEMENT, AND PLANNING

"Development of signal timing policies should be a collaborative effort between regional partners and community stakeholders, crossing jurisdictional boundaries, with the service and safety of the customer in mind at all times. Signal timing policies should be clearly documented and thoroughly communicated within an agency to those who operate and maintain the signal system" (Koonce 2008). Figure 1 illustrates the relationship of policy to the signal timing process. Operations and maintenance, along with planning, are key components of the management process.

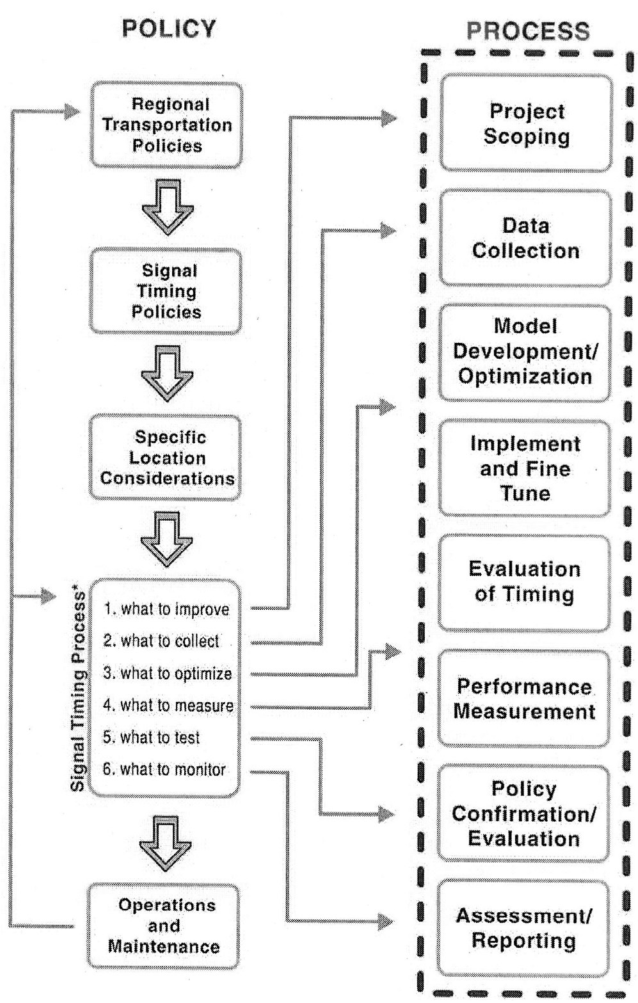


FIGURE 1 Relationship of policy to signal timing process. (*Source*: Koonce 2008.)

This chapter describes the implementation of policies.

REVIEW OF LITERATURE

Planning Processes and Management Controls

These activities may include:

- Concept of operation.
- Mission statement.
- Operations procedures.
- Compliance with Regional ITS Architecture and Standards.
- Plans for capital and operational upgrades.

Objectives, Policies, and Competition Among Objectives

Policies and objectives, along with constraints, form the cornerstones of signal timing practices. In addition to defining the objective, it is desirable for planning documentation to also describe one or more methodologies to achieve the objective, as well as performance measures and techniques to be used by the agency to obtain data to generate the measures. Table 2 illustrates the relationships among traffic signal timing processes, functions, measures of effectiveness, and possible measurement techniques. Where possible, it is desirable to include quantitative values when stating objectives. These values should be high enough to provide meaningful benefits and yet be feasible with the system features and functions provided. Objectives may conflict. For example, if transit priority is provided on an arterial, the objective of minimizing traveler delay may conflict with the objective of avoiding congestion and spillback (on the major crossing street). Resolution might require a policy that limits the aggressiveness of the priority provided. Policies and guidelines describe the agency's approach, and the strategies to be employed in signal timing and retiming relative to the prioritization of objectives and to resolve conflicting objectives.

Gordon and Braud (2009) indicate that it is appropriate for signal timing management activities and policies to emphasize outcomes. Attainment of satisfactory outcomes is accomplished by management practices that include the following:

TABLE 2
EXAMPLES OF OBJECTIVES AND MEASURES FOR TRAFFIC SIGNAL SYSTEMS

Objective Examples	Mechanism to Achieve Objective	Possible Measure	Possible Measurement Technique
Mobility, Fuel Consumption, and Emissions			
1. Reduce delay and fuel consumption for normal traffic patterns. Signal retiming may improve delay and fuel consumption by a specific minimum amount each time retiming is performed.	a. Improved signal timing. b. Improved level of traffic system control (e.g., traffic responsive, traffic adaptive). c. Real-time adjustment of timing by operator. d. Improved maintenance response time.	a. Vehicle hours delay. b. Gallons fuel reduced. c. Monitoring and tracking of citizen complaints (provide regional 311 or equivalent phone number for reporting).	a. Travel time and delay runs. b. Traffic system data. c. Simulation independent of signal timing programs. Use of traffic system data for input. d. Real-time performance monitoring.
2. Reduce delay and fuel consumption for incident conditions and special events. New signal timing plans to support these functions may improve delay and fuel consumption.	a. Signal timing—items a, b, c in 1 above. b. Support of incident management using CCTV and other information.	Same as 1. Same as 1.	Simulation. Simulation with reduction in incident clearance time.
3. Reduce emissions.	Same as 1.	kg of CO, NOx, SO_2, CO_2, VOC, particulate matter.	Derive from gallons saved.
Safety			
4. Reduce crashes resulting from signal outages.	Improved maintenance response time.	Crashes reduced.	Analysis inference techniques using response time maintenance records.
5. Reduce secondary crashes resulting from incidents.	Support of incident management using CCTV and other information.	Secondary crashes reduced.	Analysis inference techniques using reduction in incident clearance time.
Communication with Public and Public Perception of Service			
6. Improved public perception of signal and management center operations.	• Achieve other objectives. • Regular reporting to public. • Monitoring and tracking of citizens' complaints (provide regional 311 or equivalent phone number for reporting). • Develop and provide outreach material describing how traffic signals function and the benefits of active operations. • Develop website to disseminate information and reports, provide an online feedback and complaint database.	Number of calls, complaints.	Monitor number of calls, time to respond to calls, and outcome of complaints received.
7. Provide traffic information to public and private traffic information services.	Make traffic, construction, special event, incident, weather data, and CCTV signals available to traffic services, media, websites.	Rating scale.	Survey.
Ancillary Functions			
8. Serve as a diversion route for corridor operations. Goal established by stakeholders.	Items b and c in 1 above plus availability of diversion timing plans.	Same as 1 and 3.	Corridor simulations.
9. Provide preemption for emergency vehicles and railroads. Goal established by stakeholders.	Preemption equipment. It is appropriate to restrict the use of equipment so as not to cause unreasonable delay to general traffic.	Number of critical mission emergency vehicles provided preemption. Time saved by emergency vehicles.	Some preemption systems provide logs of preemptions granted.

TABLE 2 continues on next page

TABLE 2 continued

Objective Examples	Mechanism to Achieve Objective	Possible Measure	Possible Measurement Technique
10. Provide transit priority. Goal established by stakeholders.	Priority equipment used for late vehicles.	Traveler hours reduced. Variation in passenger time of arrival at designated stops reduced.	Transit records coupled with simulation with delay and delay variation criteria.
11. Support emergency evacuations. Goal established by stakeholders.	Evacuation signal timing, phasing, and lane use plans.	Availability of plans.	
		Management	
12. Projection of historical data for capital programming of future projects.	Mining of detector data.		

Source: Adapted from Gordon and Braud (2009).
CCTV = closed circuit television; CO = carbon monoxide; NOx = nitrogen oxide; SO_2 = sulfur dioxide; CO_2 = carbon dioxide; VOC = volatile organic compound.

- Assurance of qualified personnel in charge of signal timing.
- Availability and updating of a mission statement and reviews to determine how well the agency accomplishes these functions.
- Annual review by management of strategic management plans, signal timing performance, traffic system reliability, and improvement in evaluation measures.

Appendix B provides an example of the signal timing policies, guidelines, and strategies that result in desired outcomes.

In reality, all traffic signal control is policy based. The policy may be to minimize vehicle delay or vehicle stops. Policy-based traffic control can be better understood by using a hierarchy of priorities (Urbanik 2000). The hierarchy structure is, in effect, a policy developed by the agency. These policies may be determined by the agency or may be influenced by other stakeholders. Signal timing policies may relate to the following:

- Timing parameters—Examples include maximum cycle length and clearance time policies.
- Transit—If transit priority is to be provided, policies to determine the specific intersections qualifying for priority and constraints on the priority (e.g., maximum green extensions, volume-to-capacity ratio limitations on priority grants) are important.
- Preemption—Aside from rail preemption, policies to establish the emergency vehicle classes qualifying for preemption are appropriate.
- Pedestrian—Policies to establish walk speed and exclusive pedestrian intervals and phases at appropriate locations are appropriate.
- Street classification—Retiming priorities may vary by street classification (as defined by the governing locality). Many agencies retime major arterials more frequently than less traveled locations. Depending on the policies and measures selected, agencies may provide more favorable green splits and traffic progressions to major arterials.
- Optimization emphasis—Competing policy objectives may include maximizing bandwidth, emphasizing safety, minimizing delays and stops, and control of queues under saturated conditions. Emphasis may be a function of the type of network (grid, arterial, isolated), street classification, or other factors.
- Area access deterrence—Agency policies may require the avoidance of traffic assignments to certain areas such as residential areas. These are sometimes known as neighborhood traffic management programs. Signal timing strategies may play a role in these programs.

Koonce (2008) indicates that it is appropriate to review signal retiming every 3 to 5 years and more often if there are significant changes in traffic volumes or roadway conditions. It is appropriate for objective-oriented operation (Gordon and Braud 2009) to drive the frequency of signal retiming and consider the level of resources that are available to maintain target performance levels. A number of studies are identified that indicate that it is appropriate that, at a minimum, signal timing be reviewed at least every 30 to 36 months. The review is a key element to implement objective-oriented operation as described in that document. Most of the literature on previous surveys shows that the majority of the operating agencies do not conform to this guideline.

Koonce (2008) identified the following signal timing issues:

- Will all types of users (transit, freight, emergency respondents, pedestrians, vehicles, bicycles, etc.) be treated equally or prioritized at the signalized intersection?

- How frequently will signal timing plans be reviewed and updated?
- How will approaches with differing street classifications be treated?
- Will there be preferential treatment for certain movements beyond the definition of the coordinated phase (will the coordination timing plan clear all queues during each cycle for left turns and side street through movements)?
- How will intersections with deficient capacity be treated?
- What measures will be used to determine whether the timing plan is effective (vehicle stops, network delay, arterial travel speed, estimated person delay, estimated fuel consumption, transit speed, etc.) and how will they be collected?

Agencies may identify other policy issues that affect mobility and safety such as speed limit changes.

SURVEYS

Figure 2 describes the emphasis placed on signal timing approaches and practices by the agencies responding to the Puget Sound survey. Key items shown on the left of the figure include establishing effective green-band progressions, and minimizing delay and corridor throughput.

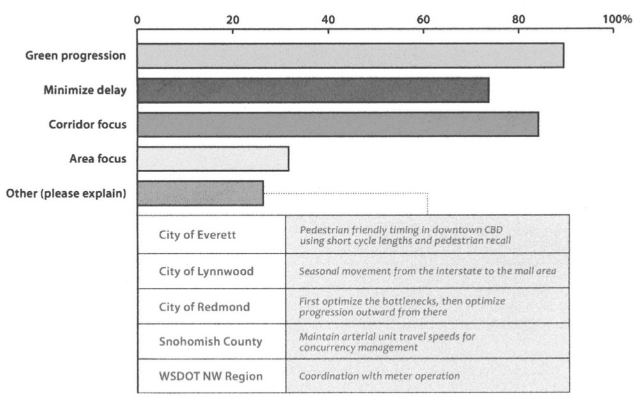


FIGURE 2 Signal timing approaches and practices in the Puget Sound area. (*Source*: Puget Sound Regional ITS Implementation Plan 2008.)

Gordon and Braud (2009) advise an annual review by management of design, operations, maintenance, and training. Approximately one-third of the responders to that project's survey indicated that they did conduct annual reviews. The report also indicates the generally poor availability of a concept of operations, mission statement, and operational procedures.

The 2007 *National Traffic Signal Report Card* indicates that:

- Almost half of the agencies (43%) reported having few or no regular, ongoing programs for collecting and analyzing traffic data for signal timing. (Because the respondents to this survey included a large number of smaller agencies, this figure may be more representative of this class of agencies.)
- Half of the agencies do not assess the quality of data collected. As a result, agencies may use faulty data to analyze and time their traffic signals.
- The overall agency score in the management area is "D."

IN-DEPTH CASE STUDIES

Four of the seven in-depth case study agencies responding to the information query are in conformance with the Regional ITS architecture and its standards, and four of the seven have documented plans for capital and operational upgrades. Four of the seven also indicated that they had prepared documented objectives. The most frequently reported objectives in the in-depth case study survey include maintenance of safety, maintenance of progression on selected arterials, and delay.

Three of the seven in-depth case study respondents conducted reviews of signal timing performance and retiming of signals if necessary within a period of 3 years. Three agencies performed these operations every 3 to 5 years, and one agency exceeded 5 years.

Signal timing by its nature is the assignment of right-of-way to competing directions and travel modes. Signal timing often requires trade-offs between various modes at an intersection, such as vehicles versus pedestrians and bicycles. These tradeoffs typically result in competing priorities, such as safe pedestrian crossing times versus maximizing automobile capacity.

The most important conflicts reported are:

- Balancing all users' needs;
- Cross-jurisdictional coordination issues;
- Pedestrian issues; and
- Disruptions caused by railroad and emergency vehicle preemption.

Less frequently reported conflicts include coordination requirements where major arterials cross, transit priority, and the use of pedestrian push buttons by bicyclists.

All of the in-depth case study respondents indicated that they conducted performance evaluations for signal timing impacts on vehicle flow. Table 3 shows the frequency of use of common measures.

Delay, stops, accidents, and fuel consumption measures are commonly used for cost versus benefit analysis. Recently, some signal timing programs have incorporated measures for congested conditions characterized by spillback or spillover across intersections and from turning bays. One program reported using the following measures:

- Queue delay—Effect of queues and blocking on short links and turning bays.

TABLE 3
AGENCY USE OF EVALUATION MEASURES FROM CASE STUDIES

Measure	Agencies Using Measure, *n* = 7
Delay	6
Stops	6
Route Travel Time	6
Accidents	5
Emissions and Fuel	4
Reliability of Travel Time	2

- Spillback capacity reduction—Reduction to the base capacity caused by a short downstream link becoming filled up. Base capacity is unimpeded capacity.
- Storage capacity reduction—Reduction to the base capacity caused when turn pockets cannot accommodate queue lengths.
- Reduced v/c ratio—Modified volume-to-capacity ratio relative to the base capacity caused by queue spillback (queues that fill a short link) and starvation (green time that is not used to service vehicles because of imperfect coordination with the upstream intersection).

STATE OF THE PRACTICE

The surveys and in-depth case studies indicated that signal timing agencies have the following concerns:

- Many agencies do not review field performance data to determine the adequacy of signal timing at intervals of 30 to 36 months, as advised for objective-oriented operation.
- Many agencies do not review design, operations, maintenance, and training practices annually as advised for objective-oriented operation.
- Many agencies do not have precise and clearly stated policies that result from objectives at the level of detail shown in Appendix B.

As more fully discussed in chapter ten, the Puget Sound Survey (Puget Sound Regional Council et al. 2008; Gordon and Braud 2009) and anecdotal data in the in-depth case studies performed under this project indicate that the combination of resource limitations and gaps in effective management are the most significant factors contributing to less than effective signal timing practices.

CHAPTER THREE

NETWORK TREATMENTS

Chapter two discussed issues at the agency level, including objectives, performance measures (covered in more detail in chapter eight), and policies. This chapter discusses signal timing issues as they apply to the control of traffic networks, including isolated intersections within the network.

Networks (sometimes called sections) are composed of signals that are coordinated as a group. The basic coordination relationship is the change of timing plans at the same time among signals in the network. Coordination generally emphasizes the use of a common cycle length or a submultiple of the cycle length (double cycling) and establishment of the offset relationship among intersections to facilitate progression of vehicles through a series of signals. Where no such relationships exist, the signal is said to be isolated. Isolated signals may be present within the physical boundaries of a network.

REVIEW OF LITERATURE

Relationship of Intersection Operation to Network Coordination

Traffic signals may be operated as pretimed or actuated signals. When using signals in networks there is a relationship between the way the signals are operated and the coordination needs of the network. The FHWA *Traffic Signal Timing Manual* (Koonce et al. 2008) summarizes the types of intersections that may be employed, as shown in Table 4.

Semi-actuated signals may be isolated or coordinated, whereas fully actuated signals usually operate as isolated signals. Day et al. (2008) showed that the use of fully actuated signals in a coordinated system may reduce delay by terminating the coordinated phase early during cycles when no continued demand is present.

Network Functional Architectures

Four levels of traffic control systems as defined by Gordon (2003) are discussed in this section. [This description builds

TABLE 4
RELATIONSHIP BETWEEN INTERSECTION OPERATION AND CONTROL TYPE

	Pretimed		Actuated		
Type of Operation	Isolated	Coordinated	Semi-actuated	Fully Actuated	Coordinated
Fixed Cycle Length	Yes	Yes	No	No	Yes
Conditions Where Applicable	Where detection is not available	Where traffic is consistent, closely spaced intersections, and where cross street traffic is consistent	Where defaulting to one movement is desirable, major road is posted <40 mph, and cross road carries light traffic demand	Where detection is provided on all approaches, isolated locations where posted speed is >40 mph	Arterial where traffic is heavy and adjacent intersections are nearby
Example Application	Work zones	Central business districts, interchanges	Highway operations	Locations without nearby signals; rural, high speed locations; intersection of two arterials	Suburban arterial
Key Benefit	Temporary application keeps signals operational	Predictable operations, lowest cost of equipment and maintenance	Lower cost for highway maintenance	Responsive to changing traffic patterns, efficient allocation of green time, reduced delay, and improved safety	Lower arterial delay, potential reduction in delay for the system, depending on the settings

Source: Koonce et al. (2008).

on the discussion in Gordon and Tighe (2005)]. Systems operated by most U.S. agencies can operate at Levels 1, 2, and 3, as described here. Operation at Level 1 requires no equipment to establish offset relationships between local intersections. Level 2 requires wireline or wireless communication with the local intersection, and Level 3 requires a complement of system detectors in addition to the Level 2 requirements.

Level 1—Time Base Coordination

Modern intersection controllers that are not physically interconnected or interconnected by wireless means have the capability to support coordinated signal timing plans through time base coordination. Progressions are achieved by relating the cycle times and offsets to a common time standard. Although time base coordination (TBC) entails a relatively low capital cost and is commonly used for backup of interconnected systems when the central computer or communication fails, it is appropriate for the system designer to consider the following limitations before selecting this approach for primary control.

- Equipment status is not provided. Consequently, equipment failure or failure to display the appropriate signal timing cannot be automatically detected at the traffic management center (TMC) or in the maintenance facility.
- Although detector data may be recorded at the controller, it is not available at the TMC in real time.
- Timing plans cannot be selected by the TMC. Selection of a timing plan that was not previously scheduled requires a visit to the intersection.
- Section-wide, traffic-responsive operation cannot be achieved.
- TBC requires an accurate common time reference among the controllers in the network. Depending on the technology used to provide this reference, frequent power interruptions may significantly disrupt coordination during and after the interruption. Although provisions for automatically resetting the controller's clock by means of global positioning system (GPS)- or radio-provided information are optionally available, most users report that it is best to perform periodic checks of the controller's clock reference. Gerken (2008) indicates that under TBC, slight drift in the clock can produce a 23% increase in delay and significant drift produces a 34% increase in delay.

Level 2—Time-of-Day and Manual Control of Timing Plans

Level 2 systems are interconnected by means of wireline or wireless communications to a central facility. They provide signal control by means of time-of-day selection of timing plans or selection of timing plans by the operator.

The in-depth case studies indicate that most U.S. traffic signal systems operate in a time-of-day mode. Typically most systems utilize three to five weekday timing plans and up to six plans for other needs such as weekends, holidays, special events, incident responses, construction, and weather. These systems utilize communications between the field controller and either the TMC or a field master controller (that may, in turn, communicate with the TMC). Thus controller status information (e.g., phase status, failure status, detector information, and, in some cases, reports developed by the field controller) are available at the TMC.

Systems may be programmed to alter phasing and phasing sequences as timing plans change, or to provide isolated intersection operation for some intersections for some periods (typically under saturated flow conditions or in some cases for late evening or early morning operation).

Level 2 systems may control signal timing in either of two ways:

- Provision of direct timing signals from the control computer at the TMC for each controller phase. Backup timing plans are stored in the controller in the event of loss of communications. Systems of this type are sometimes called centrally controlled systems.
- Signal timing plans may be downloaded and stored in the intersection controller. In some cases, the plans may be provided directly to the local intersection controller from the TMC, and in other cases the intersection controller receives its timing plans from a field master controller. The field master controller may receive plans from the TMC, or these plans may be directly programmed into the field master controller. When control can be accomplished from the TMC and data feedback is available at that location, these systems are often called closed loop systems. Most of the current systems operating in the United States are of this variety.

Level 3—Traffic-Responsive Control

Level 3 systems incorporate a traffic-responsive control strategy. These strategies use system detectors to select a plan from a timing plan library that is most appropriate to the current traffic conditions. With an appropriate complement of traffic detectors in place, both centrally controlled systems and closed loop systems are capable of providing traffic-responsive operation. Systems currently deployed in the United States generally incorporate one of the following classes of strategies.

Signature Matching Strategy This strategy develops and stores a "signature" set for each timing plan to be used. The current detector data are matched to the library of signature sets, and the timing plan with the closest match to the currently measured signature set is selected.

A "signature" consists of the following representation for each system detector selected for the computation:

VPLUSKO = $V \bullet K \bullet \phi$

Where:

VPLUSKO = signature for that detector

V = Volume

K = Constant

ϕ = Occupancy

During operation, the signature sets developed by the detector data are matched to a subset of the stored signature sets that are "allowable" for that time period. If the closest match differs from the signature set that corresponds to the timing plan currently in use, then the system transitions to the timing plan corresponding to the allowable signature with the best match.

The algorithm is designed to avoid back and forth transitioning between timing plans that are close to the selection boundary. Filtering of the volume and occupancy detector data and a "hysteresis" algorithm provide this protection. The effect is to provide a somewhat sluggish timing plan selection response to changes in the traffic demand.

A more detailed description is available in Gordon and Tighe (2005).

Parameter Selection Strategy Many traffic responsive systems assign specific detectors to identify particular parameter characteristics that are then used to select timing plans or timing plan characteristics. The following discussion is adapted from Gordon and Tighe (2005).

The specific signal timing plan selection algorithms vary among system suppliers; however, they generally provide the following features:

- System detectors in a control section are assigned to influence either the cycle, split, or offset parameter. A system detector may be assigned to one or more parameters.
- Selections of cycle, split, and offset are made based on detector data. The cycle selection, for example, would typically depend on volume and/or occupancy lying between pre-established thresholds. A cycle length is associated for each range of detector values lying between thresholds. Split and offset thresholds are similarly established.
- In some cases, traffic features such as directionality or queue presence may be used in the selection of cycle, split, and offset. System detectors may be assigned to compute these features.
- Provisions are often made for the constraint of cycle, split, and offset selections by time of day or by some other means so that the entire timing plan conforms to a plan developed by a signal timing program.

Traffic Responsive Performance Abbas et al. (2008) indicated that considerable improvement may be obtained under certain conditions with traffic responsive operation. Nelson et al. (2000) described a simulation study comparing this type of traffic responsive algorithm (TRP) with time-of-day operation (TOD). Their conclusions are as follows:

- Where traffic patterns are highly repetitive, TRP operation lags TOD owing to the time it takes to recognize the need for a new timing plan.
- Where traffic volumes fluctuate substantially, TRP has the potential of improving operation over TOD.
- Performance penalties resulting from timing plan changes do not contribute significantly to TRP disadvantages.
- The greatest problem with TRP appears to be the occasional selection of an improper timing plan.

System detectors for Level 3 operation are located sufficiently upstream of the stop line so that queues during most time periods do not back up over the detector for most of the traffic cycle. Detectors are most commonly located at all approaches to major intersections in a traffic section. Often, a single detector is located in the critical lane for an approach. Detectors may also be provided in left turn bays. Additional detectors may be provided on the major arterial at some minor intersections.

Level 4—Traffic Adaptive Control

Detectors at local intersections are commonly used to adjust the length of traffic phases in response to vehicles approaching the intersection. This type of operation is termed local traffic actuated operation and is described in chapter five. Traffic adaptive control extends the concept of rapid response to traffic networks by using flow data from detectors considerably upstream of the intersection to predict arrivals at the intersection.

Two subclasses of adaptive control for signals in networks are conventional adaptive control, and a variation that utilizes fewer detectors and is easily adaptable to conventional closed loop systems. Koonce et al. (2008) provide the following description in the *Traffic Signal Timing Manual*:

> Adaptive traffic signal control is a concept where vehicular traffic in a network is detected at an upstream and/or downstream point and an algorithm is used to predict when and where the traffic will be and to make signal adjustments at the downstream intersections based on those predictions. The signal controller utilizes these algorithms to compute optimal signal timings based on detected traffic volume and simultaneously implements the timings in real-time. This real-time optimization allows a signal network to react to volume variations, which results in reduced vehicle delay, shorter queues, and decreased travel times. Adaptive signal control autonomously adjusts signal timing parameters in real-time, to respond to actual, real-time traffic conditions. By adjusting the traffic control parameters to more closely align with traffic conditions, adaptive systems can reduce traffic delay, increase average speeds, improve travel times, and decrease travel time variability.

Small rapid timing adjustments are typically performed on the basis of a control algorithm that is optimized for some function.

Conventional adaptive control systems change the signal timing on a cycle-by-cycle basis or during the phases of a cycle.

Adaptive systems such as these require considerably more traffic detectors than is the case for Level 3 systems, thus increasing the cost of equipment and its maintenance significantly. A detailed discussion of adaptive systems is provided in Stevanovic (2010).

Koonce et al. (2008) indicated that conventional traffic adaptive systems may be most useful when the following conditions apply:

- Traffic conditions fluctuate randomly on a day-to-day basis.
- Traffic conditions change rapidly owing to new or changing developments in land use.
- Incidents, crashes, or other events result in unexpected changes to traffic demand.
- Other disruptive events, such as preemption, require a response.

Stevanovic (2010) reported that most of the agencies employing adaptive systems found performance to be generally improved, and reported a higher level of improvement for operation under oversaturated conditions.

Abbas et al. (2004) indicated that adaptive systems are not used more extensively because of their significant additional cost.

Operation and Maintenance of Adaptive Systems A recent survey of adaptive systems operations (Selinger and Schmidt 2009) indicates the following:

- The approximate cost to upgrade to adaptive control is approximately $20,000 per intersection [Costs reported in Stevanovic (2010) are considerably higher.]
- No consistent data could be identified for the average time per intersection needed to install and upgrade an adaptive system.
- 64% of the survey respondents indicated that the training effort for adaptive systems was greater than they expected.
- Of the 28 systems surveyed, 13 have been abandoned or shut down.

Saturated Intersections

When the demand volume at an intersection approaches its capacity, significant queues begin to form. These queues may exceed the storage capacity of turning bays (thus impacting flow on the through lanes) or may spill back across upstream intersections. The in-depth case studies indicate that many agencies use special measures to control the saturated intersections. If all the major phases become saturated (or oversaturated if demand exceeds capacity) and progression becomes inhibited, many agencies remove the intersection from coordinated operation and use timing that is designed to minimize spillback and lengthy queues. Research reports describe a number of strategies for control.

Strategies to Control a Saturated or Oversaturated Intersection

The in-depth case studies indicate that many agencies use the volume/density property of intersection controllers operating as isolated controllers to perform this function. Specific strategies to control isolated intersections under saturated conditions are discussed in the literature including approaches such as such intersection utilization (Li 2002) and queue length control based on vehicle storage capability (Gordon 1969), but these strategies have not seen significant operational deployment. The UTCS First Generation critical intersection control software (Gordon et al. 1996), which is used in a number of operational traffic control systems, computes green time demand for each phase based on volume and occupancy measured some distance upstream of the signal. Total available green time is then split by the ratio of the phase demands. Some adaptive systems have algorithms that apportion green time by equalizing the degree of saturation (similar to volume-to-capacity ratio). In addition, techniques have been developed to identify downstream congestion by reducing upstream green times (Smaglik et al. 2006; Beaird et al. 2006).

NCHRP Project 3-90, Operation of Traffic Signal Systems in Oversaturated Conditions, will provide guidance on the control of these intersections.

Strategies to Restrict Traffic from Entering Saturated Intersections

A somewhat different approach recognizes that demand volume at the critical intersection may be sufficiently high so that signal timing at that intersection cannot satisfactorily service these volumes, and that the resulting queues are unacceptable. These strategies reduce the flow to the critical intersection or to the area in which that intersection is located by control of upstream signals. This restriction is accomplished by timing other signals so that fewer vehicles reach the approach to the critical intersection. Lieberman et al. (2000) described the RT/IMPOST strategy. The policy's principles are: (1) the signal phase durations "meter" traffic at intersections servicing oversaturated approaches to control and stabilize queue lengths and to provide equitable service to competing traffic streams; and (2) the signal coordination (i.e., offset) controls the interaction between incoming platoons and standing queues in a way that fully utilizes available storage capacity, keeps intersections clear of queue spillback, and maximizes throughput. Lieberman has shown that this strategy is more effective at reducing delay than conventional signal timing programs.

At least one adaptive system contains a capability termed "gating" (Bretherton 2003). Gating can reduce traffic entry to links likely to become congested (trigger links) by controlling discharge flows on one or more links (restrained links). Triggers may be provided on a gradual basis.

Signal Timing Requirements for Networks

Signal Groups

For the purpose of coordinating traffic signals, an agency's signals may be grouped into networks or sections. A network is a subset of the agency's signals whose timing plans change at the same time, usually for the purpose of establishing traffic signal progressions. Signal timing techniques are discussed in chapter four. Isolated signals (signals not operating according to the network's cycle length and offset constraints) may serve to define the boundaries of the network or may operate within the physical boundaries of a network.

Some of the techniques described in the literature to establish network boundaries emphasize the distance between adjacent signalized intersections, whereas others include the comparison of through volumes with volumes that turn into the link-containing intersection. Still other techniques are based on the friction caused by adjacent land use and other factors, as well as the travel time between signalized intersections.

Appendix C discusses these techniques. There appears to be no consistent approach establishing signal section boundaries. In addition, a number of the techniques described are not well supported either by theory or by reported research. Traffic systems generally provide the ability to define a network or section of signals whose timing plans are controlled as a group. A follow-up question to the in-depth case studies assessed the techniques used for determining the boundaries of coordinated networks. Although analytic techniques such as those described in Appendix C are sometimes used, the techniques mentioned most frequently are the distance between intersections, along with judgment and traffic volumes.

Number of Timing Plans

Another key signal timing issue related to networks is the identification of the number of timing plans and their time of operation. The general practice in the United States is described by the FHWA *Traffic Signal Timing Manual* (Koonce 2008) as follows:

> The process of selecting the number of timing plans needed and the times of day when they operate may be determined through a combination of reviewing traffic data along the corridor, such as 24-hour directional traffic counts, intersection turning movement counts and traffic engineering judgment. Ideally, the following steps are used to determine the number of different plans and appropriateness for time of day changes:
>
> - For each section of the system (this is another reason why sectioning is important), select a sample of representative intersections. These might be the most important intersections in the section (if some parts of the section are more important than others), or they may be a group of intersections whose traffic conditions are typical of those existing throughout the section. In either case, the set of representative intersections are advised to include only locations that are adjacent to each other. Note that this process will require the availability of hourly counts for the entire time period being analyzed.
> - Prepare a graph that plots the traffic volume as a function of time of day for the two or three most important intersections in the sample. Using the graph, identify the AM, PM and off-peak time periods for the sample. This step is executed using judgment in the same manner that a traffic engineer would manually determine the time periods for these conditions.

Figure 3 shows an example of a graph developed by this process.

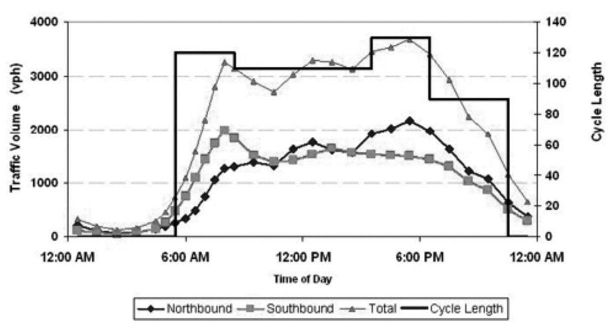


FIGURE 3 Traffic volumes summary used to determine weekday time-of-day plans. (*Source*: Koonce et al. 2008.)

An analytical approach is described by Park et al. (2004). It uses a genetic algorithm (an efficient search process) in conjunction with a signal timing program and a traffic simulation program in an iterative fashion to develop the combination of timing plans and the periods for which they are to be used.

When volumes are sufficiently high, these approaches appear to lack the sensitivity to identify flow conditions that result in delays, flow instability, and the resultant difficulty in traveling the green band. In Figure 4, Berkow et al. (2009) provide a volume versus occupancy plot that shows stable flow until 7% to 10% of occupancy is reached, at which point flow breaks down and occupancy increases much more rapidly than volume. (The detector site for this plot is a three-lane approach with the detector located some distance upstream of the stop line.) This indicates a considerable reduction in speed. It is possible that consideration of a measure of congestion or incipient congestion such as occupancy, when used in conjunction with volume, will result in an improved profile for establishing the number of timing plans and their periods of use. Table 5 shows an example of a set of timing plan periods that were developed by the use of both volume and occupancy data.

TABLE 5
TIMING PLAN INITIATION SCHEDULE FOR WHITE PLAINS, NEW YORK

	Section Type			
Time of Day	Section 1 Central Business District Grid	Section 2 Arterial	Section 3 Arterial	Section 4 Arterial
24:00 (continued)	TP1	TP1	TP1	TP1
07:30	TP2	TP2	TP2	TP2
08:45	TP3	TP3	↓	↓
09:15	↓	↓	TP3	↓
09:30	↓	↓	↓	TP3
11:00	TP4	↓	↓	↓
11:45	↓	TP4	TP4	TP4
15:30	↓	↓	TP5	↓
16:00	TP5	↓	↓	↓
16:15	↓	↓	↓	TP5
18:30	TP6	TP5	TP6	TP6
20:30	↓	TP1	↓	↓
20:45	TP1	↓	TP1	↓
21:30	↓	↓	↓	TP1

Source: Gordon (2003).

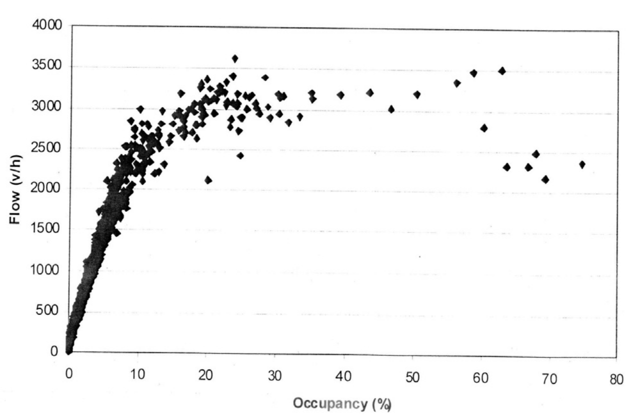


FIGURE 4 Flow-occupancy diagram for an intersection approach in Portland, Oregon.(*Source*: Berkow et al. 2008.)

STATE OF THE PRACTICE AND CONCLUSIONS

- Some progress has been made in establishing the benefits of fully actuated controllers under coordinated conditions. Guidelines to establish the conditions for this application may assist practitioners.
- No consensus appears to have been established for a methodology to establish traffic section boundaries. Research to develop a methodology would likely improve the effectiveness of coordination.
- The current guidance for establishing the number of timing plans that a network requires and the time periods for which they may be employed does not take near-saturation or oversaturated conditions into account. Although current research provides a methodology to establish time periods, this methodology is complex. Practical methodologies for establishing the number and time periods for timing plans that utilize measures of both volume and congestion may be useful to practitioners.

CHAPTER FOUR

GENERAL SIGNAL TIMING AND RETIMING CONSIDERATIONS

This chapter discusses signal timing and retiming requirements. Where signals have been previously timed, a general database structure for phasing and timing exists. As described in chapter two, good timing practices require these items to be revisited to ensure that they reflect current policies as well as the current environment. Figure 5 (Henry 2005) provides an overview of the signal timing process. Figure 6 (Day et al. 2009) emphasizes the feedback of information in the signal timing design process. The timing plans provided by the signal timing software are evaluated initially to determine whether other parameters or settings are more appropriate. The deployed timing plans are evaluated by such means as field measurements, motorist complaints, and safety records. This is often a long-term process leading to changes in the design of timing plans.

REVIEW OF LITERATURE

Collection of Data for Signal Timing

Data collection requirements as described in the FHWA *Traffic Signal Timing Manual* (Koonce et al. 2008) are summarized in Table 6. Safety issues may influence phasing and clearance intervals. In addition to the requirements shown in the table, most agencies also consider safety issues. Safety reviews and audits may consider a history of crashes to determine whether safety conditions have recently changed, and how the crash rate at the intersection relates to intersection averages that are normalized for arrival rates.

Some agencies have used existing detectors in conjunction with the data compiled by traffic signal systems to obtain the 24-hour weekly volume profiles described in Table 6 (*Using Existing Loops at Signalized Intersections for Traffic Counts* 2008).

Budget considerations may preclude the use of standard techniques for retiming signals. Henry (2005) provides a procedure that accomplishes retiming at a lower cost with some degradation in performance. Some of the measures described include the following:

- Make use of all existing information
- Use "short counts" to obtain turning movement data. Essentially this entails collecting counts for a portion of the period in question and extrapolating the data to the full period as described by Maher (2007).
- Estimate turning movement counts by using techniques that estimate turning movements from volume counts. This may be accomplished by an iterative volume balancing procedure as described in Pederson and Samdahl (1982). Software to accomplish this is available online (http://www.dowlinginc.com/).
- Low-cost retiming substitutes simple evaluative procedures such as driving the site to observe unexpected congestion patterns and observations of left turn bays for more formal evaluation procedures.

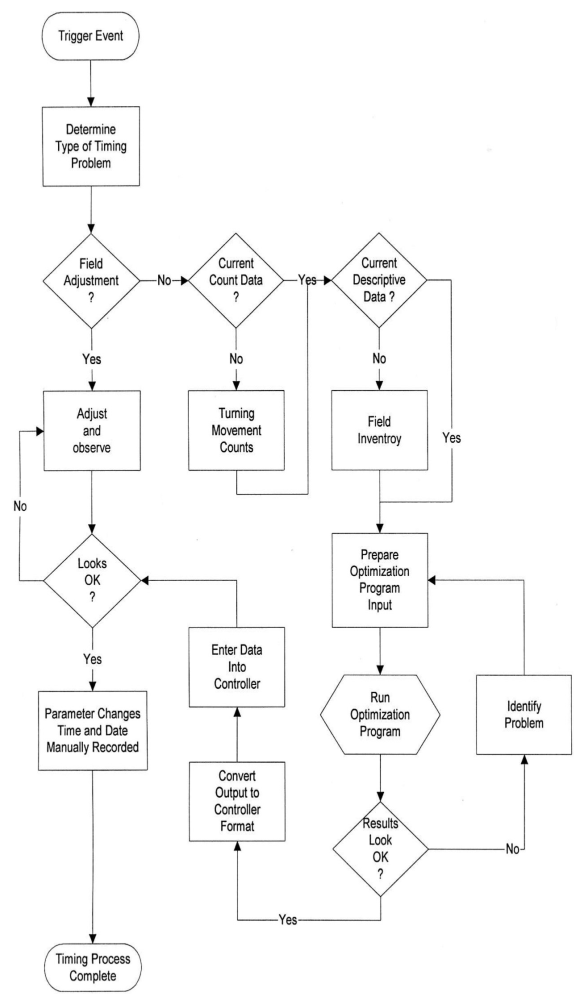


FIGURE 5 Classical approach to signal timing (*Source*: Henry 2005.)

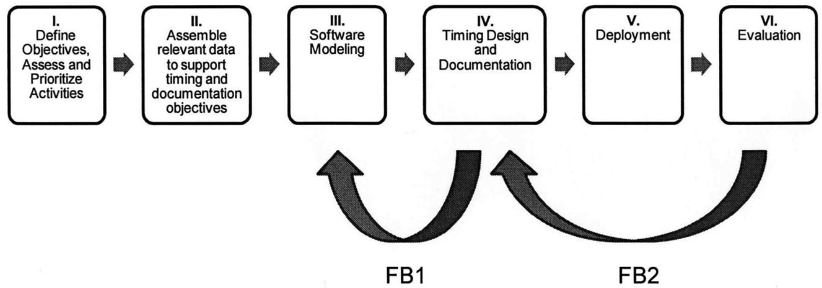


FIGURE 6 Procedural steps and feedback loops in signal timing design and maintenance. (*Source*: Day et al. 2009.)

TABLE 6
DATA REQUIREMENTS FOR SIGNAL TIMING

Type of Data	Requirement and Application
Traffic Volumes	
24-Hour Weekly Volume Profiles	Collected at critical locations in the corridor. Used to identify the number of timing plans, transition times, volume adjustment factors for developing turning movement counts, and directional distribution.
Turning Movement Counts	Turning movement counts are typically collected at each of the subject intersections under consideration for retiming. Depending on the traffic volumes and traffic patterns along the corridor, turning movement counts often only need to be conducted during peak periods, commonly the weekday morning, midday, and evening peak time periods. Daily traffic volume profiles may be used to identify the specific time periods for conducting the counts and to develop volume adjustment factors for the weekend and/or off-peak traffic volumes. At some locations, the traffic volumes may be higher or more critical during the weekend time periods, which could lead to performing turning movement counts for the weekend and the weekday time periods. Additionally, seasonal traffic patterns may need to be considered and incorporated in the scope of work. Procedures for conducting, recording, and summarizing traffic counts are described in the *Manual of Transportation Engineering Studies* (Robertson 2000). Intersection turning movement counts are collected for representative traffic periods. Traffic count may include a count of all vehicular traffic at the intersection, as categorized by intersection approach (i.e., northbound, southbound, etc.) and movement (i.e., left-turn, through, or right-turn movement), pedestrians, and vehicle type (including transit). If heavy vehicles are significant, the vehicular count may be further categorized by vehicle classification. The presence of special users at the intersection (e.g., elderly pedestrians, school children, bicycles, emergency vehicles, etc.) may also be documented.
Vehicular Speed	Data on vehicular traffic speed may be gathered to identify the approach speeds to the intersection. This is especially important in determining the signal phasing and clearance requirements.
Travel Time Runs	Travel time runs can be used to calibrate the existing analysis model and to compare the corridor operations before and after the new timings are implemented. Travel time runs are collected by driving the subject corridor and recording the delay, stops, and running time using electronic equipment.
Intersection Geometry and Control	A site survey may be conducted to record relevant geometric and traffic control data. These data include: number of lanes, lane width, lane assignment (i.e., exclusive left turn, through only, shared through and right turn, etc.), presence of turn bays, length of turn bays, length of pedestrian crosswalks, and intersection width for all approach legs. A condition diagram is an effective method for recording this information.
Field Review	Key elements to consider are location and operation of signal equipment, intersection geometry, signal phasing, intersection operations, vehicle queuing, adjacent traffic generators, posted speed, and/or free flow speed. The free flow speed will assist with calibrating the traffic model and establishing offsets that reflect the traffic conditions.
Existing Signal Timing	The existing signal timing helps the traffic engineer understand what currently exists in the field and provides a baseline for improvement.

Source: Koonce et al. (2008).

ANALYSIS OF THE INTERSECTION

Assessment of Phasing

The *Manual on Uniform Traffic Control Devices* (*MUTCD* 2009) defines a signal phase as "the right of way, yellow change, and red clearance intervals in a cycle that are assigned to an independent traffic movement or combination of movements."

Modern U.S. practice for signal control organizes phases by grouping them in a continuous loop (or ring) and separating the crossing or conflicting traffic streams by the time they are allowed to operate, either by making the movements sequential or adding a barrier between the movements. The ring identifies phases that may operate one after another and are typically conflicting phases organized in a particular order. For instance, it may be desirable to separate the traffic traveling through the intersection in the northbound direction from the southbound left turn movement. A change interval and clearance time is used to separate that movement in time.

In Figure 7, a "barrier" is used to separate the east–west movements from north–south movements to avoid operating conflicting movements at the same time. It is also used to define a relationship between the rings to ensure compatible movements. The barrier represents a reference point in the cycle at which a phase in each ring has reached a point of termination; both rings must cross the barrier simultaneously (Koonce et al. 2008). Figure 7 shows the most commonly employed phasing diagram for major intersections. Guidance on selection of phase sequences is provided by Koonce et al. (2008). Koonce has also summarized (Figure 8) prior guidance on determining the need for a left turn phase based on previous work (Orcutt 1993; Kell 1998). Other sources may use somewhat different sight distance data from that shown in Figure 8.

These guidelines are sometimes superseded by the requirements of state *Uniform Manuals on Traffic Control Devices*. In addition, they do not provide guidance for the possible elimination of conflicts with pedestrians.

Consideration of Safety Issues

The in-depth case studies have rated safety issues as among the most important factors in the operation of intersections. Crash experience is a warrant in the *MUTCD*. Many agencies use accident modification factors (AMFs), also known as crash reduction factors (CRFs), to estimate the effect of a design change in the crash rate. Monsere et al. (2006) describe a number of these factors. *NCHRP Project 17-25 Crash Reduction Factors for Traffic Engineering and ITS Improvements* provides comprehensive guidance on these factors.

An "x" indication in Table 7 (Koonce et al. 2008) identifies the relationship of crash characteristics to signal timing issues.

Enhancement of pedestrian safety includes special pedestrian intervals (leading and lagging) and incorporation of an exclusive pedestrian phase. Although leading pedestrian intervals are often cited as improving pedestrian safety, the literature also shows cases where pedestrian–vehicle conflicts have increased when leading pedestrian intervals have been deployed (Hubbard et al. 2008).

Although the *MUTCD* provides for a reduction in the speed for the pedestrian walk signal clearance interval from 4.0 feet per second to 3.5 feet per second, this lower speed had already been adopted by a number of the agencies responding to the in-depth case study questionnaire. Measures such as these to enhance pedestrian safety often adversely affect vehicle green time and cycle length. Hua et al. (2009) reported that the most effective pedestrian safety improvements for the locations

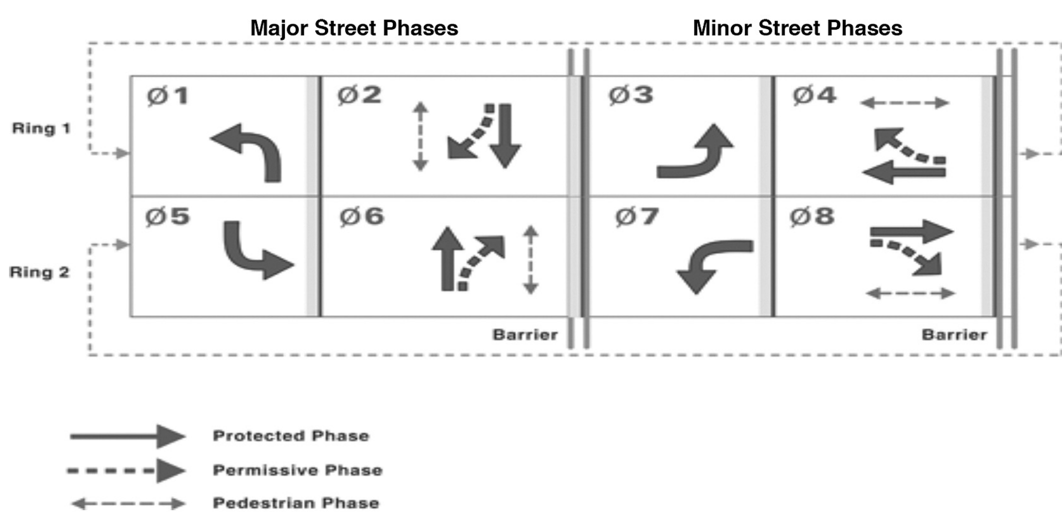
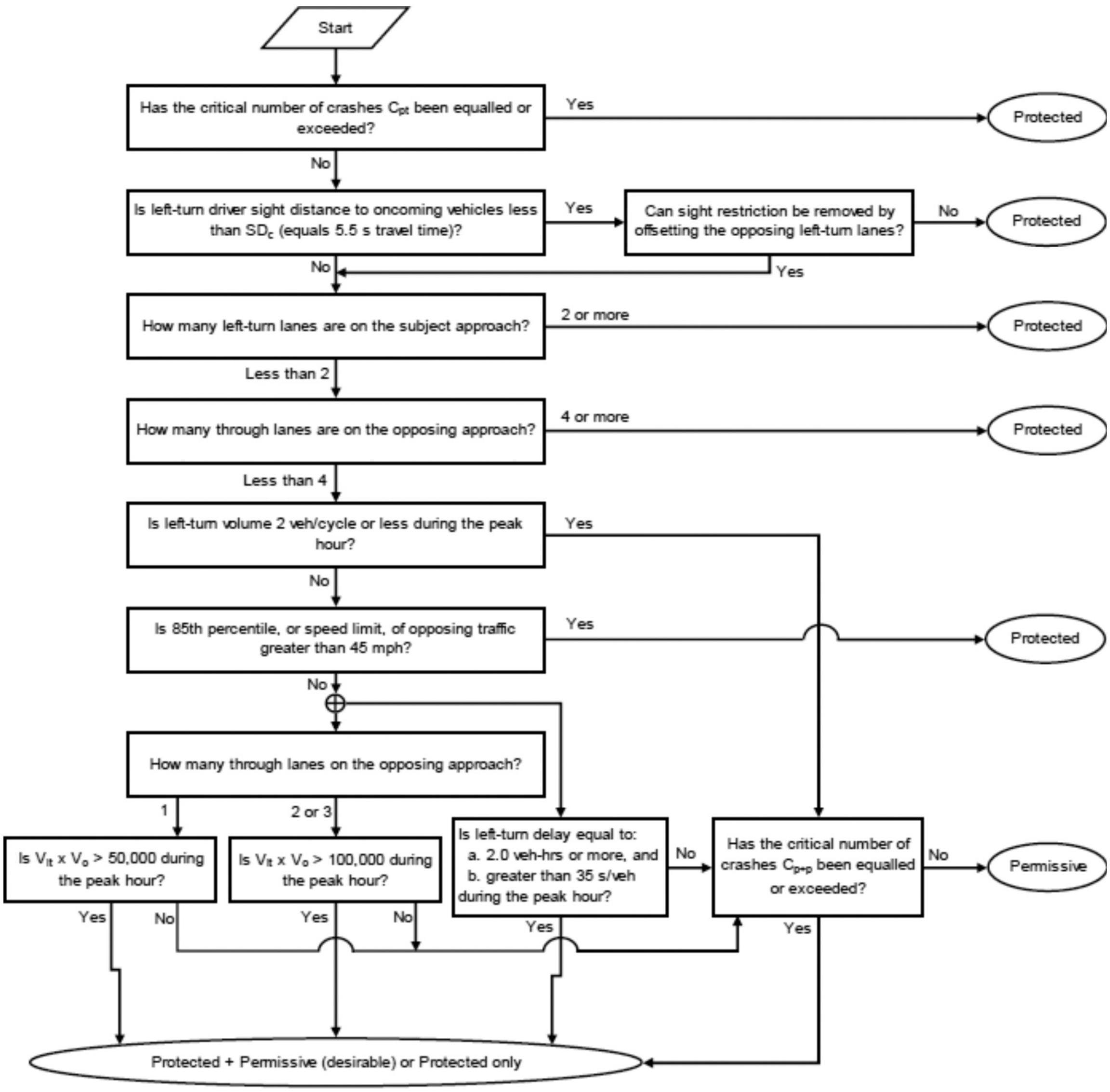


FIGURE 7 Typical vehicular and pedestrian movements at an eight-phase dual-ring intersection. (*Source*: Koonce et al. 2008.)

studied included the use of flashing beacons and push button actuation, in-street pedestrian signs, vehicle detection to actuate signal timing, leading pedestrian intervals, portable changeable message speed limit signs, and "Turning Traffic Must Yield to Pedestrians" signs.

DETECTOR PLACEMENT

Placement of detectors depends on the local and system requirements for the intersection. Local requirements include the phases to be actuated, the approach speeds, and



Number of Left-turn Movements on Subject Road	Period During Which Crashes are Considered (years)	Critical Left-Turn-Related Crash Count When Considering Protected-only, C_{pt} (crashes/period)	Critical Left-Turn-Related Crash Count When Considering Prot.+Perm, C_{p+p} (crashes/period)
One	1	6	4
One	2	11	6
One	3	14	7
Both	1	11	6
Both	2	18	9
Both	3	26	13

Oncoming Traffic Speed Limit (mph)	Minimum Sight Distance to Oncoming Vehicles, SD_c (ft)
25	200
30	240
35	280
40	320
45	360
50	400
55	440
60	480

Variables

V_{lt} = left-turn volume on the subject approach, veh/h

V_o = through plus right-turn volume on the approach opposing the subject left-turn movement, veh/h

FIGURE 8 Guidelines for determining the potential need for a left-turn phase. (*Source*: Koonce et al. 2008.)

the queues expected at the intersection. System requirements depend on the type of traffic responsive or traffic adaptive coordination strategy employed. Review of existing detector placement is critical whenever any of these factors change. Guidance is provided in Gordon and Tighe (2005), Klein et al. (2006), and Koonce et al. (2008).

RETIMING TOOLS AND MODELS FOR THE NETWORK

Retiming Tools

Most agencies use a signal timing software program to minimize a delay-based objective function or to maximize arterial through progression. These programs require a database consisting of the geometrics of the signalized intersections and the physical relationships among intersections, lane use, and phasing information. Phase-specific parameters such as clearance periods, pedestrian walk periods, and actuated controller parameters are to be entered. Signal timing programs also generally require average turning movement volumes for the period in which the timing plan will be used. In many cases, migration of data to and from the signal timing program and the traffic control system is facilitated by the use of an open standard data format known as the Universal Traffic Data Format (UTDF). There are six file formats specified by the UTDF (*Signal Timing Process Final Report* 2003):

- VOLUME stores volume counts
- TIMING stores timing plan information that varies by time of day
- PHASING stores timing plan information that doesn't change
- TIMOFDAY stores a weekly schedule of when to use timing plans
- LAYOUT stores intersection locations and connections
- LANES stores lane and fixed information.

Although HCS (Highway Capacity Software), which programs *Highway Capacity Manual* relationships, is not a signal timing program, agencies often use it as a basis for timing isolated intersections.

Simulation Programs

Simulation programs are sometimes used to predict and evaluate the effects of signal timing optimizations. *Macroscopic models* often accompany signal timing programs and are

TABLE 7
SAFETY RELATIONSHIPS TO SIGNAL TIMING

	Collision with Another Vehicle					Single-Vehicle Collision				
Signal Timing Change	Angle	Head-On	Rear-End	Sideswipe—Same Direction	Sideswipe—Opposite Direction	Collision with Bicycle	Collision with Parking Vehicle	Collision with Pedestrian	Over-turned	Run Off Road
Provide Left-Turn Signal Phasing	x	x	x	x	x					
Optimize Clearance Intervals	x		x							
Restrict or Eliminate Turning Maneuvers (including right turns on red)	x	x	x	x		x		x		
Employ Signal Coordination	x		x					x		
Implement Emergency Vehicle Pre-emption	x	x	x	x	x	x	x	x		
Improve Traffic Control of Pedestrians and Bicycles			x			x		x		
Remove Unwarranted Signal			x			x		x		
Provide/Improve Left-Turn Lane Channelization	x	x	x	x	x					
Provide/Improve Right-Turn Lane Channelization	x		x	x		x		x		

Source: Koonce et al. (2008).

used to assist in evaluating the impacts of signal retiming. *Microscopic models* simulate the vehicle following characteristics for each vehicle. They are sometimes used to determine the effects of retiming on flow characteristics that may vary from cycle to cycle (e.g., the behavior of queues in left turn bays). Dynamic visualizations are usually included in the simulation software. Microscopic models may be used to simulate the effects of such special functions as signal preemption and transit vehicle priority. Jeannotte et al. (2004) provide guidance on the selection of models and other tools.

CHAPTER FIVE

REQUIREMENTS FOR SIGNAL RETIMING

Requirements for timing actuated signals, together with other requirements and agency practices, are discussed in this chapter.

REVIEW OF LITERATURE

Actuated Timing Periods

Three key timing periods related to actuated phases are minimum green, passage time (vehicle extension time), and maximum green.

Minimum Green

Decisions on the minimum time that the green is displayed should be based on a number of factors. These factors, identified by Koonce et al. (2008), are shown in Table 8. Guidance for the settings is provided by Koonce et al. (2008), Henry (2005), and Tarnoff and Ordonez (2004).

Passage Time (Vehicle Extension Time)

Passage time is used to find a gap in traffic for which to terminate the phase. Essentially it is the setting that results in a phase ending prior to its maximum green time during isolated operation. If the passage time is too short, the green may end prematurely, before the vehicular movement has been adequately served. If the passage interval is set too long, there will be delays to other movements at the intersection. The appropriate passage time used for a particular signal phase depends on many considerations: type and number of detection zones per lane, location of each detection zone, detection zone length, detection call memory (i.e., locking or nonlocking), detection mode (i.e., pulse or presence), approach speed, and whether lane-by-lane or approach detection is used. Ideally, the detection design is established and the passage time is determined to ensure that the "system" provides efficient queue service and safe phase termination for higher-speed approaches (Koonce et al. 2008).

Kyte et al. (2009) show that long detection zones for vehicles can permit the values of passage time settings to be reduced. For example, if the detection zone is 60 ft, the probability that a gap will exceed this value is only 5%. Thus the passage time can be reduced to zero or near zero with a very low probability that the next vehicle in the queue will not be detected.

Maximum Green

The maximum green parameter represents the maximum amount of time that a green signal indication can be displayed in the presence of conflicting demand. Maximum green is used to limit the delay to any other movement at the intersection and to keep the cycle length to a maximum amount. It also guards against long green times resulting from continuous demand or broken detectors. Ideally, the maximum green will not be reached because the detection system will find a gap to end the phase, but if there are continuous calls for service and a call on one or more conflicting phases, the maximum green parameter will eventually terminate the phase. A maximum green that is too long may result in wasted time at the intersection. If its value is too short, then the phase capacity may be inadequate for the traffic demand, and some vehicles will remain unserved at the end of the green interval (Koonce et al. 2008).

Guidance for maximum green time settings include the following:

- A percentage increment over the average time to clear the phase may be used to ensure that most of the vehicles will be serviced during the phase. Koonce et al. (2008) provides specific settings.
- The maximum green setting is based on the equivalent optimal pre-timed timing plan based on delay minimization. The minimum-delay green interval durations are multiplied by a factor ranging from 1.25 to 1.50 to obtain an estimate of the maximum green setting (Skabardonis 1998).
- Guidance for maximum green time G_{max} (in seconds) provided by Bonneson et al. (2009) is as follows:

Major-Road Through Phase:

$G_{max,\ thru}$ = Larger of: (30, $G_{min,\ thru}$ +10, $0.1 \times V$)

TABLE 8
FACTORS CONSIDERED WHEN SETTING THE MINIMUM GREEN INTERVAL

Phase	Stop Line Detection?	Pedestrian Button?	Considered in Establishing Minimum Green? Driver Expectancy	Pedestrian Crossing Time	Queue Clearance
Through	Yes	Yes	Yes	No	No
		No	Yes	Yes*	No
	No	Yes	Yes	No	Yes, if actuated
		No	Yes	Yes*	Yes, if actuated
Left-Turn	Yes	Not applicable	Yes	Not applicable	No

*Slightly modified factors are provided by Bonneson et al. (2009).
Source: Koonce et al. (2008).

Where:

V = peak-period volume per lane (vehicles per hour).

Minor-Road Through Phase:

$G_{max,\ thru}$ = Larger of: (20, $G_{min,\ thru}$ +10, 0.1 × V)

Left-Turn Movement Phase:

$G_{max,\ left}$ = Larger of: (15, $G_{min,left}$ +10, 0.5 × $G_{max,\ thru}$)

- Nichols and Bullock (2001) advise the following:

Max 1 = 1.3 * morning peak split time

Max 2 = 1.3 * evening peak split time

Very long green times and cycle times may not provide the additional throughput expected by the reduction in lost time (Denney et al. 2009).

Volume-Density Control

A detector placed considerably upstream of the intersection can anticipate the number of vehicles requiring service during the next green period. Volume-density control provides for a *variable initial* period in place of the minimum green time to service these arrivals, thus more accurately fitting the green period to the arriving platoon. The effect on the initial timing should be to increase the timing in a manner dependent on the number of vehicle actuations stored on this phase although the signal is displaying yellow or red (NEMA 2003). This increment is termed *added initial*.

With the detector considerably upstream of the stop line, the period for the vehicle to reach the stop line is considerably greater than with stop line detection. *Gap reduction* timing reduces the allowable gap between vehicle calls in a controlled way to enable preference to be given to vehicles waiting on an opposing phase.

Koonce et al. (2008) provides guidance for a number of settings for volume-density control.

Relationship of Phase Intervals

The 8-phase dual ring controller shown in Figure 7 is used extensively. Its many options and sequences, although well defined individually, exhibit numerous complex relationships whose interactive effects may be difficult to visualize. Figure 9 shows one example of timing interval relationships. Head et al. (2007) developed a precedence graph model for better understanding these relationships. The complexity of this interaction in a timing plan with multiple phases, overlaps, time of day, traffic responsive, and preemption plans is a substantial challenge for nearly all agencies.

Pedestrian Issues

MUTCD 2009 reduces the speed used to time the pedestrian clearance interval from 4.0 ft/s to 3.5 ft/s. The *MUTCD* also indicates that the sum of the walk and pedestrian clearance intervals should not result in a speed exceeding 3 ft/s.

Clark et al. (2006) indicated that the minimization of pedestrian–vehicle conflicts is critical to pedestrian safety. They propose the following classifications to measure the effect of conflicts and procedures for measuring these classifications:

- *Non-Conflicting Pedestrian Crossing*: Pedestrian leaves the curb during the walk phase and arrives at far side curb by the end of the pedestrian clearance phase. During the crossing, no delay or evasive maneuver was needed.
- *Compromised Pedestrian Crossing*: Pedestrian reaches the far side curb by the end of the pedestrian clearance phase but is delayed by turning vehicles or takes evasive action in response to a turning vehicle.
- *Failed Pedestrian Crossing*: Pedestrian did not reach far side curb by the end of the pedestrian clearance.

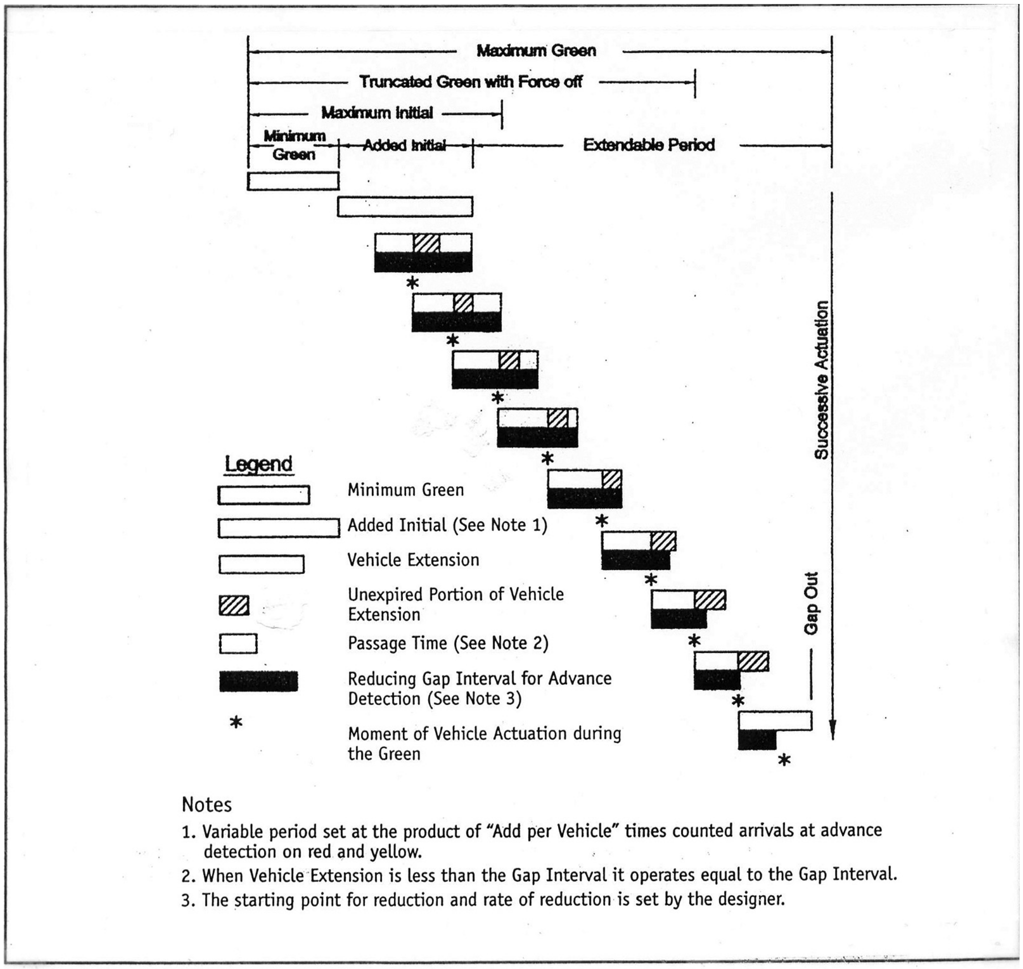


FIGURE 9 Green interval for volume-density operations. (*Source*: Pline 2001.)

SURVEYS AND IN-DEPTH CASE STUDIES

Actuated Timing Periods

Minimum Green

Figure 10 shows the use of minimum green times as reported by the Tarnoff and Ordonez (2004) survey.

Factors for determining minimum green as reported by Tarnoff and Ordonez (2004) include:

- Driver reaction times;
- Intersection width;
- Time to move one car through the intersection;
- Different fixed policies for main-street left, main-street through, and cross street;
- Observation;
- 5 s with stop bar detectors, 15 s without;
- Grade and type of traffic;
- Initial vehicle startup time;
- Traffic volume; and
- Minimum driver reaction time.

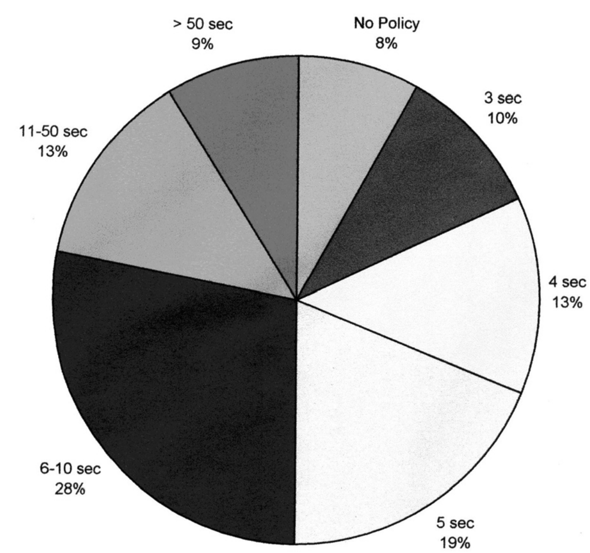


FIGURE 10 Minimum green time at isolated intersections. (*Source*: Tarnoff and Ordonez 2004)

When there is a pedestrian demand but no push button is provided, the minimum green is advised to include the times for the pedestrian walk and pedestrian clearance intervals.

This is a significant contributor to the wide variation in minimum green in Figure 10.

Although the presence of a stop line detector theoretically may eliminate the need for a minimum green, most engineers believe that at least a short minimum green is needed to satisfy driver expectation. This time may vary among practitioners from 2 to 15 s (Bonneson and McCoy 1993). Koonce et al. (2008) provides guidance for this expectancy time based on intersection classification.

Passage Time (Vehicle Extension Time)

Factors for determining passage time as reported by Tarnoff and Ordonez (2004) include:

- Field evaluation;
- Speed and volume;
- Detector type and location;
- Single standard value;
- Fixed value (values of 2, 3, 3.5, and 7 s were reported);
- Length of detection zone;
- Time for vehicles to cross intersection minus 4 s; and
- Time needed for slow moving vehicle to pass over loops and cross the intersection.

Maximum Green

Figure 11 shows the use of maximum green times as reported by the Tarnoff and Ordonez (2004) survey. The relatively large percentage of long maximum green times may achieve less than expected benefits, as indicated earlier in the chapter.

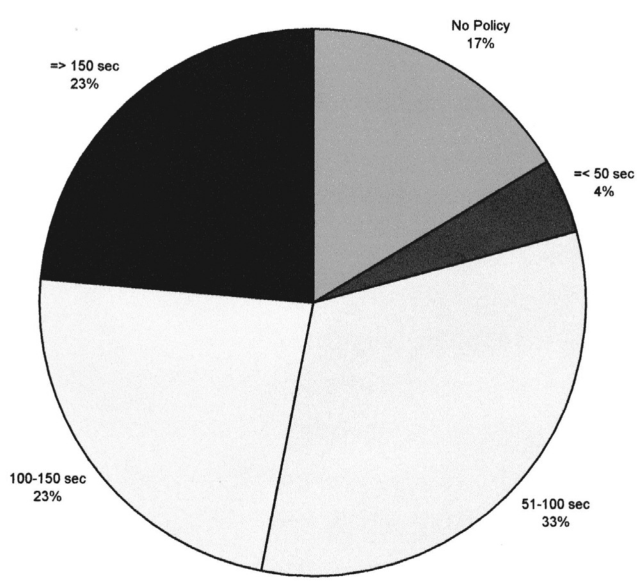


FIGURE 11 Maximum green time at isolated intersections. (*Source*: Tarnoff and Ordonez 2004.)

Techniques for determining maximum green time as reported by Tarnoff and Ordonez (2004) include:

- Traffic demand;
- 1.5 times the optimized green time;
- Volume/capacity ratio;
- Maximum vehicles per hour for the intersection;
- Level-of-service;
- Field observations;
- Desired (optimized) split;
- "Rules-of-thumb, delay, density, and backups";
- Proportional to demand using a very long cycle length;
- Queue clearance; and
- Citywide standard.

Some practitioners use occupancy to assist in determining maximum green time as relatively high occupancies indicate the presence of unsatisfied demand at the end of the phase.

Intersection Priorities and Triggers for Retiming

The in-depth case studies indicate that although some agencies retime signals periodically, others use triggers to initiate the retiming process. These triggers include:

- Significant changes in land use;
- Requests from the public;
- Traffic conditions such as saturation or spillback; and
- Detector or CCTV information that indicates changes in volume or congestion patterns.

Respondents indicated a strong predisposition to time major arterials more frequently. Other factors mentioned include areas with high growth, critical street segments and intersections, and accident histories. A small number of respondents indicated that no preferential treatment was provided. Appendix D describes a systematic approach to signal retiming prioritization employed by one agency.

Frequency of Signal Retiming

Most of the in-depth case study participants indicated that they retimed signals at 3- to 5-year intervals. Several of the recent surveys addressed this issue but in slightly different ways.

The Puget Sound Survey (*Puget Sound Regional ITS Implementation Plan* 2008) indicated the following:

- 22% of the agencies retimed signals at 2-year intervals
- 67% of the agencies retimed signals at 3- to 5-year intervals
- 11% of the signals retimed signals at intervals of 5 years or greater

Tarnoff and Ordonez (2004) also provide data in Table 9.

TABLE 9
AVERAGE RETIMING INTERVAL

Average Retiming Interval	Percent of Respondents
More Frequently than Every 3 Years	42
Around 5 Years	18
Around 10 Years	5
More than 10 Years	35

Source: Tarnoff and Ordonez (2004).

Rephasing Techniques and Issues

Phasing requirements and signal timing requirements are generally reviewed at the same time. The in-depth case studies identified the relative importance of techniques and issues considered during phasing reviews as shown in Table 10.

TABLE 10
TECHNOLOGIES AND ISSUES LEADING TO REPHASING

Highly Important	Less Important
Collision Analysis	Critical lane analysis
Volume Warrants	Separation of conflicting movements
Avoidance of Pedestrian Conflicts	Green band considerations
Left-turn Observations	

Source: Case studies.

Signal Retiming Methodologies

All of the agencies participating in the in-depth case studies and almost all of the agencies responding to the information query utilize a signal timing program to develop the timing settings. Tarnoff and Ordonez (2004) also indicated that 52% of respondents to this survey used some sort of manual technique. All of the in-depth case study participants and most of the respondents to the Tarnoff and Ordonez survey use a simulation program to assist in pretesting signal timing plans.

According to the 2007 Traffic Signal Report Card, nearly 60% of agencies perform a comparative analysis of cycle lengths, offsets, phase sequence, and other timing parameters as part of the process for the evaluation and implementation of signal timings. Sixty-one percent reported having strong or outstanding procedures for considering different signal phase sequences to minimize interruption of traffic progression during the evaluation of timing for a coordinated system. Agencies also reported using actuation and off-peak timing practices to improve flow during periods of light traffic. Two-thirds (68%) of the agencies reported having strong or outstanding procedures for timing actuated controllers. Sixty-nine percent reported having strong or outstanding procedures for using operational strategies that promote smooth and efficient traffic movement along an arterial during periods of light traffic flow or at night.

Timing Plan Use

This section reports the results of in-depth case studies and surveys that indicate the number of timing plans that agencies commonly employ.

Table 11 and the following discussion employs the combined results of the in-depth case studies and the survey conducted under Gordon and Braud (2009).

TABLE 11
AGENCY USE OF DAILY TIMING PLANS

Number of Daily Timing Plans Employed	Percent of Agencies
3	13
4	56
5	13
6	6
7	13

Source: Gordon and Braud (2009).

All of the agencies responding to both studies employed weekend/holiday/special event plans, usually two to three timing plans of this type. Seventy-six percent of the agencies provided timing plans for diversion, evacuation, or other emergencies.

The in-depth case studies indicated that the most common way of establishing time periods is by examining volume and occupancy data.

The results of the survey performed by Tarnoff and Ordonez (2004) showing the use of timing plans for various purposes are presented in Table 12.

Minor Geometric Improvements

In some cases traffic flow may be improved through the use of minor geometric improvements. Five of the seven in-depth case study respondents indicated that they reviewed intersections for minor geometric improvements either periodically, as needed, or in response to complaints. All of the agencies retimed the signals after minor geometric modifications.

STATE OF THE PRACTICE AND CONCLUSIONS

Passage Time

Recent research (Kyte et al. 2009) highlights a strong relationship between detection zone length and the best passage time settings.

TABLE 12
TIMING PLAN USE

Type of Plan	Description	Percent of Respondents
a.m. Peak	Weekday morning rush hour	100
p.m. Peak	Weekday evening rush hour	100
Off Peak	Typically a weekday plan used all other times	86
Incidents	Special plan for diverted freeway traffic during incidents	33
Weekends	Saturdays and/or Sundays	66
Holidays	Special plans when holiday traffic differs from weekend traffic (e.g., heavy shopping after Thanksgiving)	57
Weather	Plans for snow, fog, or other weather that affects traffic flow	19
Special Events	Plans for sporting events or other events that have an impact on traffic flow patterns	56
Other		10

Source: Gordon and Braud (2009).

Long Maximum Green and Cycle Times

Figure 11 shows that 23% of isolated signalized intersections are programmed for green times equal to or greater than 150 seconds. Denney et al. (2009) indicated that these very long green times may not provide the improved throughput that was expected from their use. Further research should include substantiation using a larger database and resultant guidance for these parameters.

Interrelationships of Phase Intervals

As described by Head et al. (2007), the effects of the interrelationships of options for the phase settings of actuated controllers are complex and difficult to predict under some circumstances. Current information on these interrelationships may be of only limited assistance; further research to improve information for practitioners would be useful.

Volume-Density Operation

Although descriptions of operation are available along with guidance for timing, additional research might include information on the conditions for which volume-density operation offers performance improvements.

CHAPTER SIX

METHODOLOGIES FOR FIELD IMPLEMENTATION OF TIMING PLANS

After timing plans have been developed in the office, they must be transferred to the field controllers. The actual field timing plans should be checked against the intended plans to ensure that they are being properly displayed. Because the processes and models for developing timing plans have limitations in how well they represent actual conditions, it is appropriate for the timing plans to be fine tuned in the field, particularly with regard to such conditions as satisfaction of left turn requirements and spillback across upstream intersections.

REVIEW OF LITERATURE

Methodologies for Transferring Timing Plans to Intersection Controllers

The methods for transferring timing plans to field controllers depend on the architecture of the traffic system, the availability of interconnect at the field controller, and agency practices. The methodologies may include the following:

- In-system architectures that control the timing by directly providing a signal from the central computer on a second-by-second basis (central control), only the backup timing plans need be installed in the field controller at the intersection.
- Where a central computer is available, and controllers and communication to the field controller are available (such as for closed loop systems), timing plans may be downloaded from the central computer into the intersection controller. Many system architectures require a master controller in the field. In this case, timing plans are first downloaded into the field master controller and then into the intersection controller. The timing plans in the controller may be uploaded into the central computer to ensure that the installed timing plan is correct. In most cases, the traffic systems compare the uploaded plans to the programmed plans and identify discrepancies.
- Laptop computers, notebook computers, and PDA devices are often available from traffic system suppliers to facilitate the download of timing plans into intersection signal controllers in the field.
- Timing plans may be entered into the field controller through a keypad.

Fine Tuning of Timing Plans

The models used for timing plan development described in chapter four are generally *macroscopic* models; that is, they use average parameters such as volume and capacity along with link parameters to establish the signal timing values. Models of this type generally do not consider the cycle-to-cycle variations in traffic demand. These variations may result in conditions such as spillback from turning lanes and across closely spaced intersections, resulting in considerable disruption to traffic flow. A fine-tuning process is appropriate to ensure that the timings address real-world conditions.

Koonce et al. (2008) and Henry (2005) strongly advise field reviews of signal timing plans in the form of intersection observations and route driving runs, and appropriate timing adjustments.

The following techniques may be used at the central facility to assist in the fine-tuning process.

- Use of *microscopic* simulations. These simulations model the behavior of each vehicle through car-following models and lane-change models. Statistically based traffic generation models provide inputs to the traffic network, and the results of the modeling period may be obtained as computer reports. The simulated motion of the vehicles may be observed by the traffic engineer on a visual display. Recent technology has enabled actual field controllers to be used in the office in conjunction with the simulations to provide a more realistic model for field controller operation. Examples of the use of this technology are provided by Yun et al. (2007), Smadi and Birst (2006), and Balke and Herrick (2004).
- Use of performance monitoring systems. As described in more detail in chapter nine, performance monitoring systems (see Liu and Ma 2008, and Balke et al. 2005) use actual data collected by field controllers to provide an estimate of the intersection performance. They require an additional component in the field controller cabinet.
- Use of high-resolution data collectors to tabulate phase volume-to-capacity ratios, progression quality, and intersection delay. Smaglik et al. (2007) show how a controller can be used to collect the appropriate data, and indicate that the necessary algorithms can be

embedded in the controller. Detectors considerably upstream of the intersection are used to implement these algorithms.

IN-DEPTH CASE STUDIES

The frequency of usage of these techniques for inserting timing plans into controllers, as determined by this project's in-depth case studies, is provided in Table 13.

TABLE 13
FREQUENCY OF USE OF TECHNIQUES FOR INSERTING TIMING PLANS

Technique	Number of Agencies Reporting Use, *n* = 7
Direct Control From Central Computer	1
Download From Central Computer	3
Download From Laptop, Desktop, or PDA	5
Manually Insert	4

Source: Gordon and Braud (2009).

All of the in-depth case study agencies indicated that they verified the timing plan settings by field observation and that they performed fine tuning using field observations (one agency indicated that relatively little attention was paid to minor intersections). Four of the agencies indicated some use of CCTV information. Two agencies reported using simulation and field detector data to assist in fine tuning.

CONCLUSIONS

There appear to be no serious problems in properly installing and verifying timing plans in field controllers. Techniques for facilitating fine tuning by field processing of data collected by controllers are emerging and will assist in this process. Smaglik et al. (2007) indicated that a standard to provide for data collection software common to all suppliers would facilitate this process.

CHAPTER SEVEN

PERSONNEL RESOURCES AND COST FOR IMPLEMENTATION OF SIGNAL TIMING PLANS

Agencies may retime signals using their own personnel or may contract part of or all of the retiming effort to consultants. This chapter describes the personnel qualifications and resources necessary to retime signals.

REVIEW OF LITERATURE, SURVEYS, AND IN-DEPTH CASE STUDIES

Personnel Qualifications

The appropriate use of signal timing tools and the quality of the entire signal timing process depend, in large measure, on the capabilities of the personnel responsible and the adequacy of staffing. Guidance for personnel qualifications and training is provided by Row and Tarnoff (2005) and by Gordon and Braud (2009). The latter document advises that at a minimum, signal timing and operations be supervised by personnel with Professional Engineer and Professional Traffic Operations Engineer qualifications.

Staffing Levels and Cost

The ability to retime signals according to the performance-based criteria of objective-oriented operation depends on the agency's resources and staff. The following discussion provides various perspectives on the requirements necessary to accomplish this as well as the current practices. Because engineering staffs have various responsibilities in addition to signal retiming, it is unlikely that an understaffed agency will be able to perform high-quality retiming.

A work load of 75 to 100 signals per engineer for agencies that operate a minimum of 150 signals is advised by Gordon and Braud (2009). Smaller agencies will likely require fewer signals per engineer because economies of scale may be difficult to realize. Giblin and Kraft (2000) similarly advise the assignment of 75 to 100 signals per engineer. Table 14 summarizes the traffic engineering staffing levels reported by the Puget Sound survey and the in-depth case studies. The average agency size for the in-depth case studies was considerably larger than for the Puget Sound survey: 62% of the responding agencies responding to the Puget Sound survey believed that their staff size was inadequate.

TABLE 14
NUMBER OF SIGNALS PER TRAFFIC ENGINEER

Reference	Number of Signals per Traffic Engineer	
Case Studies	Average: 185	
	All 19 agencies in survey	5 agencies >150 signals
	Average = 67	Average = 93
	Median = 62	Median = 81

Source: Puget Sound Regional ITS Implementation Plan (2008).

Figure 12 shows a breakdown for the number of person hours appropriate for signal timing tasks as determined by the *Traffic Signal Timing and Operations Survey* (ITE 2009).

The in-depth case study questionnaire was structured to identify the components of the effort and cost to perform the signal timing tasks. Five of the in-depth case study agencies provided the detailed information for Figure 13, the average person hours expended, and Figure 14, the approximate costs of contracted signal retiming.

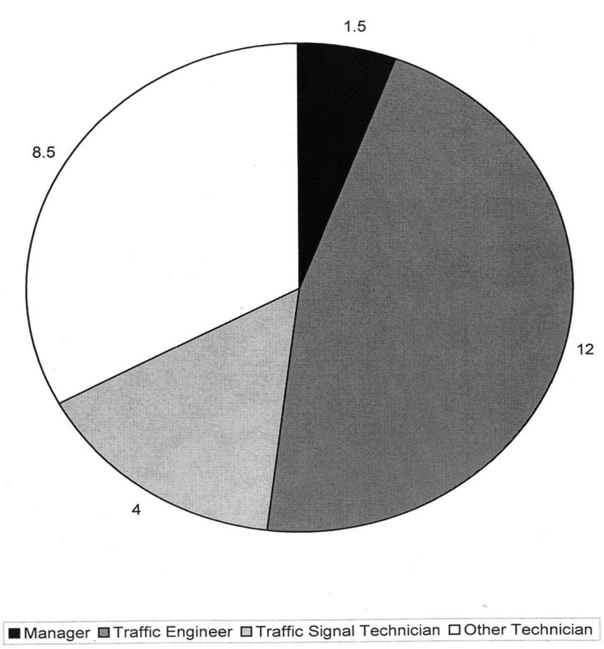


FIGURE 12 Person hours to retime an intersection (redrawn).
Source: Traffic Signal Timing and Operations Survey (2009).

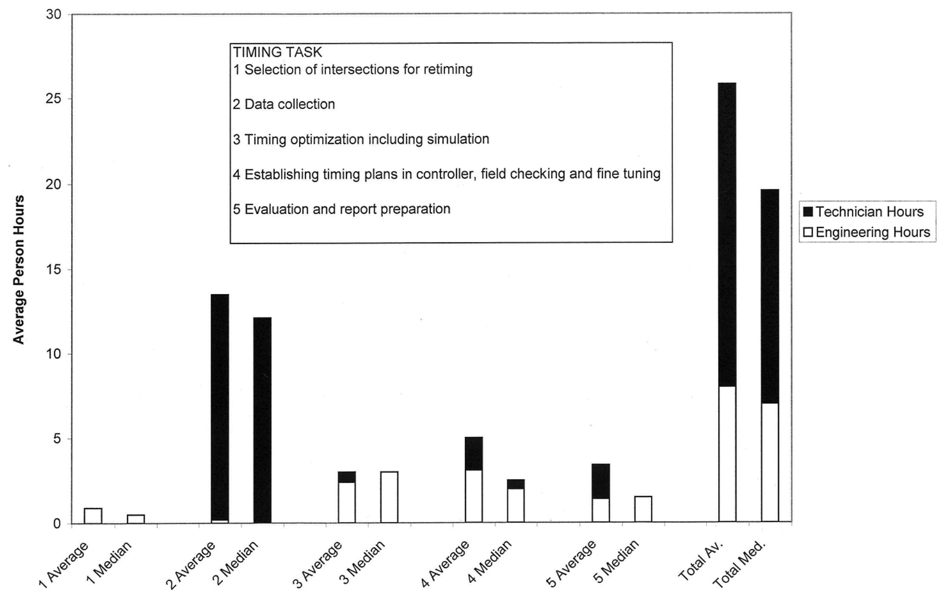


FIGURE 13 Person hours appropriate for signal retiming tasks.

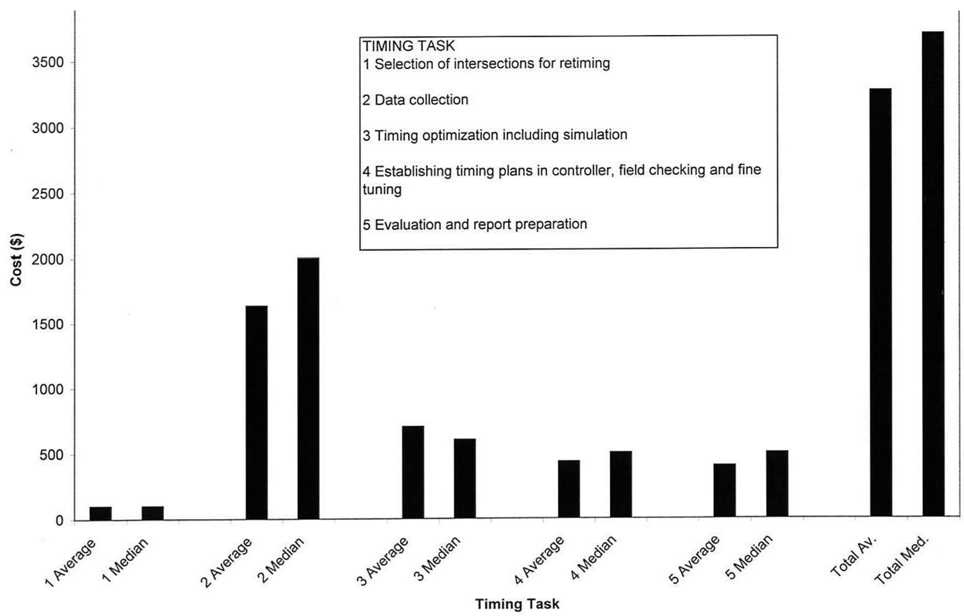


FIGURE 14 Cost for contracted signal retiming tasks.

Other sources, including Tarnoff and Ordonez (2004) and W. Hood's personal communication (2009), reported the average cost of signal retiming to generally be \$2,500 to \$3,500 per intersection (note that the Tarnoff and Ordonez survey preceded the in-depth case studies by about 5 years).

CONCLUSIONS

Although the work load levels for the agencies in the Puget Sound survey generally fall within the advised guidelines, most of those agencies perceived that they were understaffed.

The person hours expended in retiming intersections varies considerably among agencies. A representative average value is 26 person hours per intersection.

Although the cost of purchasing signal retiming services also varies widely (variations are functions of the number of timing plans and differences in the level of services utilized by agencies), most agencies obtain the retiming services that they require for \$3,700 or less per signal.

CHAPTER EIGHT

PERFORMANCE MEASURES

This chapter covers the functions of performance measures, followed by a discussion of the different classes and applications of performance measures for signal timing. The methods for obtaining these performance measures are also discussed. Research currently being conducted under NCHRP Project 3-79a, Traffic Signal Performance Measures, will significantly enhance these findings.

NCHRP Synthesis 311 (Shaw 2003) provides a detailed review of performance measures used for transportation. For the purpose of signal timing evaluation, most agencies use measures that are specifically oriented to that application as described in this chapter.

FUNCTIONS OF PERFORMANCE MEASURES

- *Performance monitoring.* This includes the effect of signal timing on users of the intersection, including private vehicle occupants, pedestrians, transit vehicles, and bicycles. From a signal retiming perspective, these measures usually relate to the objectives established by the agency for retiming purposes. Table 2 in chapter two provides examples of the relationships between objectives and measures. Delay for each user class and safety are usually key measures.
- *Measures used to assist in retiming the signals.* Although related to performance monitoring measures, they are intended to assist traffic engineers with signal retiming.

Figure 6 (in chapter four) shows how performance measures relate to the retiming process itself (FB1) and to performance monitoring (FB2).

PERFORMANCE MONITORING MEASURES

Vehicle Performance

All of the techniques used to obtain values for the measures are subject to errors that result from the measurement technique, or from the processes used to compute the measure from data that are collected. The presence of these errors should be considered when the measures are used for management purposes such as resource allocation. When consistent measurement and computation techniques are used over a period of time, the values developed are useful to estimate the relative performance improvement provided by signal retiming.

The *2010 Highway Capacity Manual* (HCM) identifies *level of service* (LOS) as a measure for signalized intersections. LOS depends on control delay and whether the volume-to capacity ratio is greater than 1.0. Control delay includes delay associated with vehicles slowing in advance of an intersection, the time spent stopped at an intersection approach, the time spent as vehicles move up in the queue, and the time needed for vehicles to accelerate back to their desired speed. Table 15 shows the LOS for signalized intersections.

TABLE 15
HCM 2010 LEVEL OF SERVICE CRITERIA

	Level of Service by Volume to Capacity Ratio	
Control delay (s/veh)	≤1.0	>1.0
≤10	A	F
>10–20	B	F
>20–35	C	F
>35–55	D	F
>55–80	E	F
>80	F	F

Source: 2010 Highway Capacity Manual.

Commonly employed vehicle performance measures include volume, travel time, travel time reliability, delay, stops, throughput, queue length, and progression quality. Crashes are a key measure. Evaluations usually include the components of vehicle emissions.

A number of traffic signal controllers incorporate the capability for measures of effectiveness reports. One supplier's controller has the capability to provide the following parameters (Balke and Herrick 2004): volume, stops, delays, and utilization (the average time that the green interval lasts for each phase).

Gordon and Braud (2009) indicated that objectives and performance measures are important to achieve quality traffic signal system operation. They describe the following criteria for signal timing measures:

- Span the traffic system and agency functions to encompass the different requirements of all agencies.
- Be measurable or answerable using existing information, information that can be readily obtained, or information that may take some effort to collect but that is vital to the determination of the capability of the traffic system relative to the objective-oriented operation criteria described in the report.
- Minimize the need for subjective judgment to accomplish evaluation.

The Knoxville Regional Transportation Planning Organization uses the following evaluation measures in their congestion management system (Congestion Management System).

- Volume-to-capacity ratio (present and future)
- Roadway corridor and segment travel time (peak versus off-peak)
- Stopped delay at intersections (from travel time study)

All of the in-depth case study respondents indicated that they conducted performance evaluations for signal timing impacts on vehicle flow. The frequency of employment of common measures in the signal timing process is provided in Table 16.

TABLE 16
AGENCY USE OF EVALUATION MEASURES FROM CASE STUDIES

Measure	Agencies Using Measure, $n = 7$
Delay	6
Stops	6
Route Travel Time	6
Crashes	5
Emissions and Fuel	4
Reliability of Travel Time	2

Pedestrian Performance

Measures for pedestrians at signalized intersections have undergone significant changes between HCM 2000 (*Highway Capacity Manual 2000*) and HCM 2010.

Because pedestrians are key intersection users as well, evaluation measures have been developed and used for this purpose. The pedestrian LOS measures provided in HCM 2000 are based on pedestrian delay as computed by the equation.

$$\text{Pedestrian delay} = 0.5(C - g)^2/C$$

Where:

C is cycle length and

g is green time.

Hubbard et al. (2008) indicated that this equation does not account for pedestrian/vehicle conflicts resulting from vehicles (primarily right turning vehicles) turning into the pedestrian crosswalk during the pedestrian interval. In response to this and other research, HCM 2010 develops a LOS based on a *pedestrian perception index* for the intersection. This index is based on a number of factors, including intersection and crosswalk geometrics, vehicle volumes, and speed.

Hubbard et al. (2008) proposed *compromised pedestrian crossings* as a measure of pedestrian service level. A compromised crossing occurs if pedestrians are delayed by turning vehicles or change their travel path or speed. The measure is provided by:

Compromise $\%_{\text{Non-CBD}}$ = 0.040 (right turn flow rate in pedestrian interval in vph)

Compromise $\%_{\text{CBD}}$ = 0.026 (right turn flow rate in pedestrian interval in vph).

Signal Preemption

Traffic signal timing for railroad signal preemption relates to the connection between the activation of the protection devices and the traffic signal clearances that ensure queue clearance from the tracks. Balke et al. (2005) discussed these issues and introduced a truncation exposure index to estimate the potential effect of unprotected periods.

Emergency vehicle preemption increases delay to general traffic. A key parameter that determines the extent of the delay is the classes of vehicles for which preempt is provided. All seven of the in-depth case study agencies provide preempt service to fire vehicles, four to ambulances, and two to police vehicles.

Delay to general traffic also depends on the type of algorithm employed by the controller to restore coordination at the termination of the preempt state (Park et al. 2008; Bullock and Cantarella 1998).

MEASURES USED TO ASSIST IN RETIMING SIGNALS

To provide a basis for improved signal timing, Balke and Herrick (2004) identified the following measures for the evaluation of signal timing plans:

- The average number of times a phase was activated in a given evaluation period
- The average number of vehicles served per cycle during a given evaluation period
- The average number of vehicles stored per cycle during a given evaluation period (residual queue)
- The probability of a vehicle having to stop at an approach during a given evaluation period
- The percentage of overloaded cycles (or cycle failures) during a given evaluation period

Bullock et al. (2008) provided examples of how the following performance measures defined in the HCM 2000 may be used to improve signal timing: progression adjustment factor, volume-to-capacity ratio per phase, and components of intersection saturation.

These measures are further discussed in Day et al. (2010).

Recent signal timing programs have incorporated measures for congested conditions characterized by spillback or spillover across intersections and from turning bays. As an example, the measures currently provided by one program include:

- Queue delay—Effect of queues and blocking on short links and turning bays.
- Spillback capacity reduction—Reduction to the base capacity caused by a short downstream link becoming filled up. Base capacity is unimpeded capacity.
- Storage capacity reduction—Reduction to the base capacity caused when turn pockets cannot accommodate queue lengths.
- Reduced v/c ratio—Modified volume-to-capacity ratio relative to the base capacity.

CHAPTER NINE

EVALUATION OF SIGNAL TIMING PERFORMANCE

This chapter discusses the techniques used by agencies to evaluate the benefits obtained by retiming traffic signals, and how the economic and emissions impacts of these benefits are estimated.

The measures in Table 17 are commonly used to evaluate the benefits associated with the implementation of revised signal timing plans. This chapter discusses the principal methods for obtaining these measures.

TABLE 17
COMMONLY USED EVALUATION MEASURES

Measure	Type of Benefit
Delay	Traveler utility
Travel Time and Travel Time Reliability	Traveler utility
Stops	Traveler utility
Crashes	Safety
Fuel Consumption	Out of pocket cost
Emissions	Environment

REVIEW OF LITERATURE

Techniques Used for Travel Time and Delay Evaluation

Observations of Vehicle Travel Behavior

Methods include travel time studies for test vehicles and intersection observations of delays and queues. Comparisons may be made before and after signal retiming. Methods, sample sizes, and data collection procedures for route travel times and delays as well as intersection delays are, for example, provided by Robertson (2000). A number of states also provide procedures for collection and analysis of field data (*Manual on Uniform Traffic Studies* 2000). GPS is commonly used to facilitate the data collection and processing associated with floating vehicle studies. Although traditionally used by traffic engineers, these methods are generally labor intensive and are therefore often expensive to implement.

Software is available to assist in the collection and processing of data from floating vehicles. The software enables the user to study the detailed movement of test vehicles. It computes evaluation measures such as travel time, delay, fuel consumption and emissions.

Recent technology advances enable vehicles serving as probes to be used for travel time determinations. Technologies such as toll tag systems, Bluetooth readers, license plate matching systems, and systems using cellular telephones and GPS may supply data to provide travel time to motorists and evaluate travel time performance. Evaluations using these technologies can be economically performed at more frequent intervals than floating vehicle studies. Using special test vehicles, Fontaine and Smith (2005) described the error properties of probe-generated data. Wasson et al. (2008) indicated that the use of unexpected routes by vehicles on surface streets requires special data processing techniques to eliminate these vehicles from the estimation. They also indicated that the use of a vehicle identification format known as *media access control* facilitates the data processing appropriate to identify vehicles for travel time estimation.

Estimates of Delay and Other Measures Using Traffic Signal Systems

With more extensive use of traffic detectors and centrally monitored traffic control systems it may be possible to collect the data necessary to develop signal system evaluation measures in an automated and less labor intensive way than that described earlier. However, data collected by conventional traffic systems are usually in the form of periodic values for volume, occupancy, and speed at the detector locations. These data do not directly correlate to the commonly used measures shown in Table 17. One approach to obtaining these measures is to incorporate advanced software into the traffic controller, as discussed in chapter eight. Another approach is to use archived user data system technology.

The National ITS Architecture provides for the establishment of the Archived Data User Service (ADUS) to control the archiving and distribution of ITS data. ADUS provides the Historical Data Archive Repositories and controls the archiving functionality for all ITS data. FHWA maintains an ADUS website (ADUS) that references ADUS standards and other background material. An *archived data management system* (ADMS) is an application that takes the data from the archive and analyzes them or formats them in a way to facilitate subsequent analysis.

Several ADUS/ADMS systems have been devised to develop evaluation parameters based on the traffic controllers' phase indications, phase calls, and detector inputs. Balke et al. (2005) describe the Traffic Signal Performance Monitoring System, that develops measures for isolated intersections, whereas Liu and Ma (2008) report on the SMART-SIGNAL system. Figure 15 shows the SMART-SIGNAL system's architecture. The figure shows the data processing as located at the University of Minnesota's facility. The local data collection units are SMART-SIGNAL equipment that must be added to the controller cabinet.

The parameters generated by the SMART-SIGNAL system include intersection delay, stops, LOS, queue, and corridor travel time. Figure 16 shows an example of the type of evaluation that it is possible to develop, the delay on an arterial improved by signal retiming. Real-time delay estimation models using high-resolution controller data have also been developed by Sharma et al. (2007, 2008).

Simulation Estimates of Performance

Evaluations may be conducted by the use of microscopic simulation. Because of the difficulty in relating simulation results to actual field performance, simulation is most often used to choose alternative timing plans or alternative control modes for one or more sets of traffic conditions. An example of such an approach is described by Wilson et al. (2006), who simulated a traffic adaptive traffic signal system and the field controller response to signal control and traffic actuations. A general microscopic traffic simulation was modified using an application's programming interface to model the traffic system's control algorithms and detectors. Using this simulation, Figure 17 shows the results for an arterial for three different signal system modes. The SCATS Isolated VA mode is an adaptive vehicle actuated mode that changes cycle length and split. The SCATS Masterlink Mode changes offset as well. It is seen from the upper figure (which shows delay under average volume conditions) that delay is fairly similar for all three modes when the actual volume is close to the volume used to develop the timing plans. The lower figure shows that when the traffic volume differs from the volume used to develop the fixed time plans, both the value

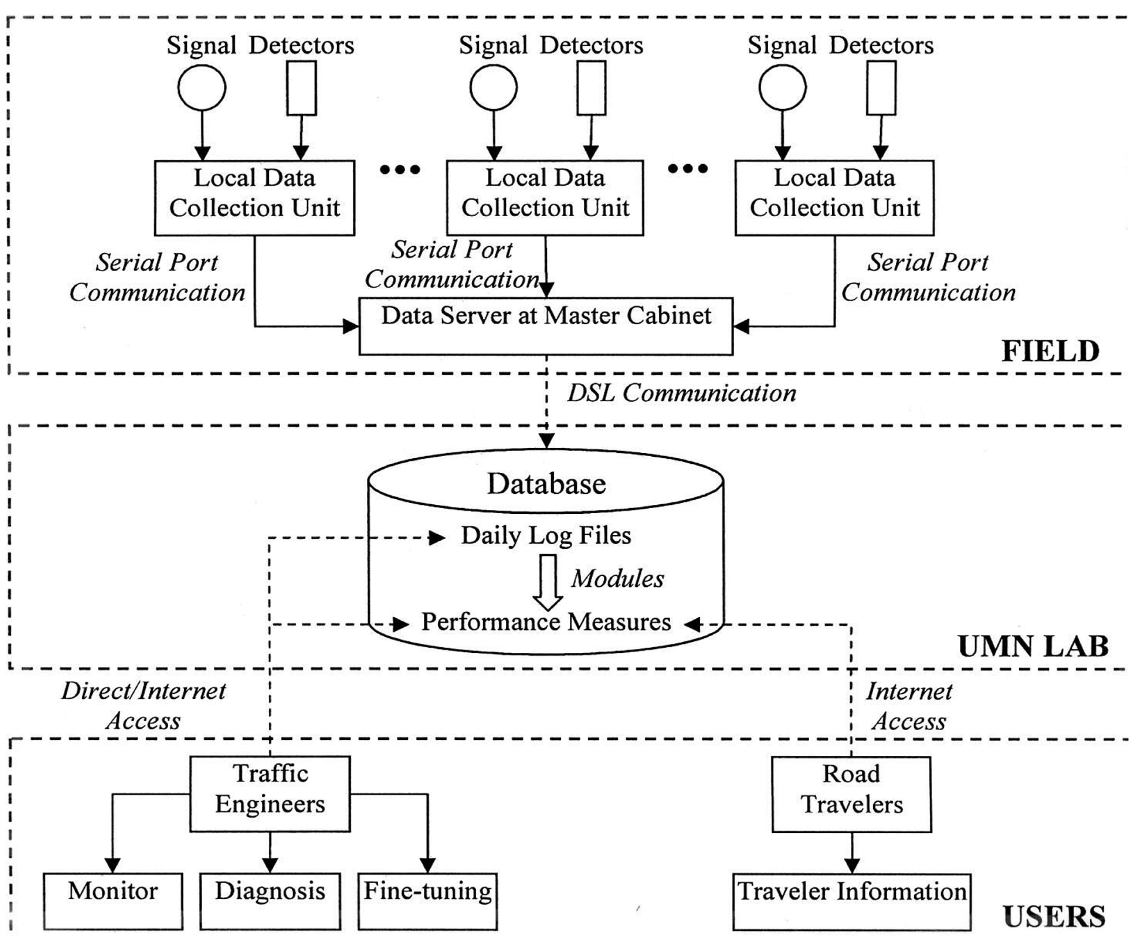


FIGURE 15 The SMART-SIGNAL system architecture. (*Source*: Liu and Ma 2007.)

of delay and its variation is considerably smaller for the adaptive modes.

Safety

Changes in signal timing are sometimes used to improve safety at intersections. Conversely, changes to improve traffic flow may have adverse effects on safety. The crash rate and its trend when changes are made in signal timing, phasing, and intersection design are key measures of safety and change in safety. Some agencies provide overall crash rate statistics for intersection type and crash cause as an ongoing process. Figure 18 is an example (NYSDOT 2009) that provides intersection accidents per million entering vehicles (MEV). Data such as these establish a baseline for the analysis of intersection safety.

Actual intersection crash rates may be statistically analyzed in conjunction with these data to identify high crash locations. The analysis may result in establishing priorities for remedial action (*2008 Annual Evaluation Report*).

Comparison of intersection crash performance with average overall rates and crash types may provide a basis for improvement of signalized intersection treatment. As shown in the matrix in Table 7, Koonce et al. (2008) correlate crash characteristics with the types of signal timing changes that may reduce crash rates.

Fuel Consumption and Emissions

Fuel Consumption

Fuel consumption rates depend on the mix of vehicle types and on the mix of engine technologies employed. These parameters are expected to change in the future as recently revised fuel consumption standards take effect. The price of fuel affects travel demand and consequently influences fuel consumption.

The following is a model for fuel consumption used at this writing by two signal timing programs:

F = TotalTravel * k1 + TotalDelay * k2 + Stops * k3

k1 = .075283 – .0015892 * Speed + .000015066 * Speed^2

k2 = .7329

k3 = .0000061411 * speed^2

F = fuel consumed in gallons

Speed = cruise speed in mph

TotalTravel = vehicle miles traveled

TotalDelay = total signal delay in hours

Stops = total stops in vehicles per hour.

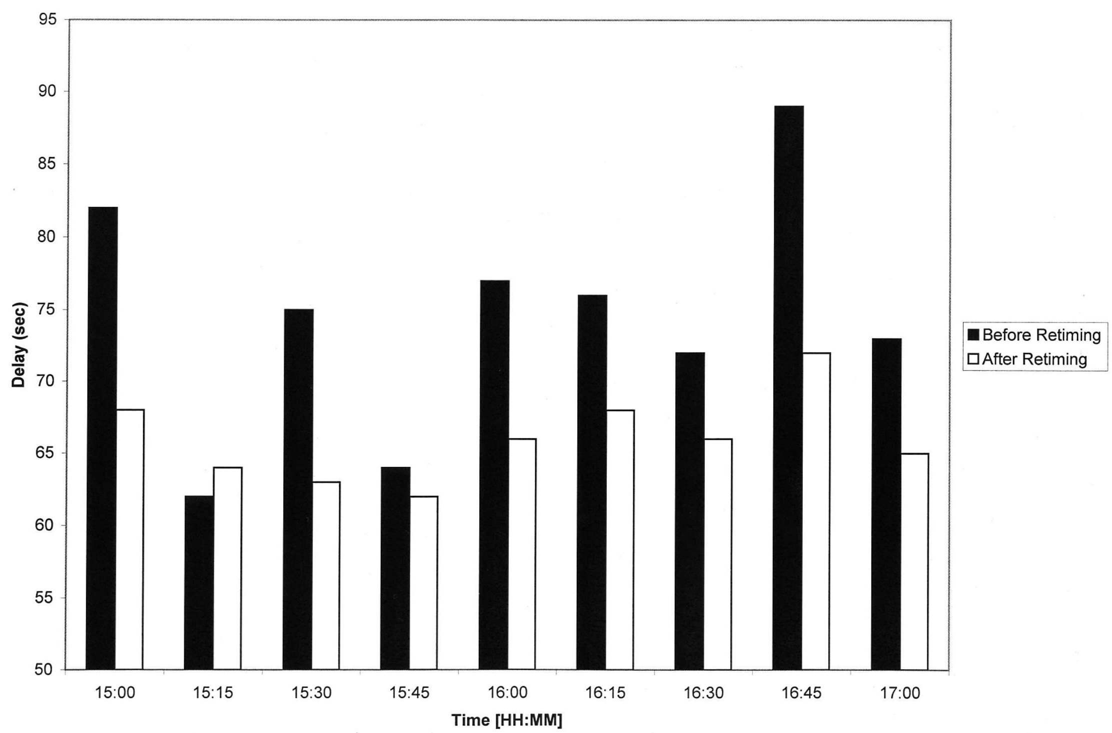
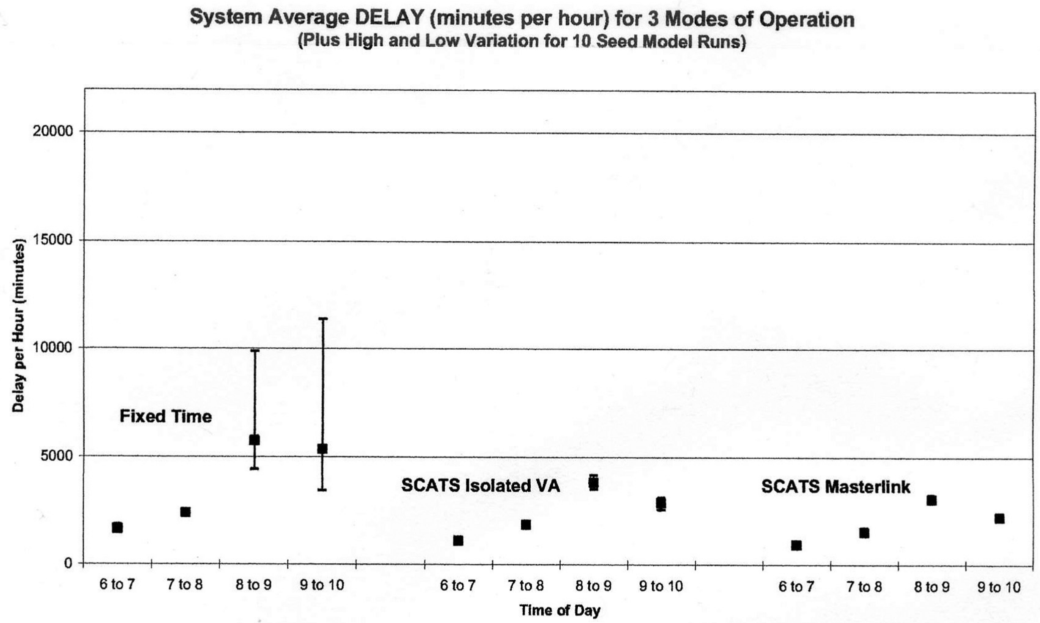


FIGURE 16 Delay averaged over 10 weekdays from 3 p.m. to 5 p.m. (redrawn). (*Source*: Liu and Ma 2007.)



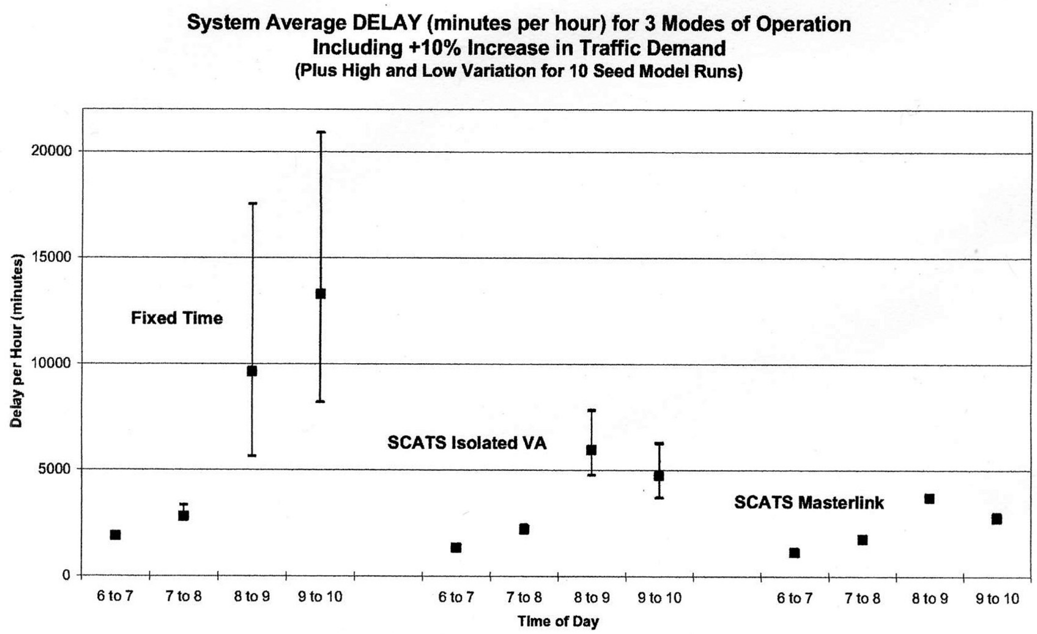


FIGURE 17 Delay for different control modes and volume variations. (*Source*: Wilson et al. 2006.)

Because of the model's assumptions concerning vehicle types and engine technologies, caution is advised in using the model. It is best used for a comparison before and after signal retiming. (This is only one of several models currently in use and may not represent the latest data.)

Emissions

Emissions models used by signal timing programs often use fuel consumption as a key parameter. The emissions commonly used as measures include carbon monoxide (CO), nitrogen oxides (NOx), and volatile oxygen compounds (VOC). Emission rates currently used by two signal timing programs (data provided by an unpublished letter to the FHWA from the Oak Ridge National Laboratory) are given by:

CO = F * 69.9 grams/gallon

NOx = F * 13.6 grams/gallon

VOC = F * 16.2 grams/gallon

F = fuel consumption (gallons).

The anticipated use of a new emissions simulation program (MOVES 2009) may result in a change in these values.

AVERAGE INTERSECTION ACCIDENT RATES FOR STATE HIGHWAYS BY INTERSECTION TYPE
(BASED ON ACCIDENT DATA JANUARY 1, 2007 TO DECEMBER 31, 2008)

INTERSECTION TYPE RURAL FUNCTION CLASS	ALL TYPES ACC/MEV	WET ROAD ACC/MEV	LEFT TURN ACC/MEV	REAR END ACC/MEV	OVER-TAKING ACC/MEV	RIGHT ANGLE ACC/MEV	RIGHT TURN ACC/MEV	HEAD ON ACC/MEV	SIDE-SWIPE ACC/MEV
3 LEGGED INTERSECTIONS									
SIGNAL ALL LANES	0.22	0.04	0.02	0.06	0.01	0.03	0.01	0.01	0.01
SIGN ALL LANES	0.15	0.03	0.01	0.03	0	0.01	0	0	0
NO CONTROL ALL LANES	0.09	0.01	0.01	0.01	0	0.01	0	0	0
4 LEGGED INTERSECTIONS									
SIGNAL ALL LANES	0.50	0.09	0.06	0.11	0.02	0.11	0.02	0.01	0.01
SIGN ALL LANES	0.31	0.06	0.02	0.04	0.01	0.08	0.01	0	0
NO CONTROL ALL LANES	0.12	0.02	0	0.01	0.01	0.02	0	0	0.01
ON RAMP (ALL CONTROL)									
MERGE W/ 1 LANE	0.07	0	--	--	--	--	--	--	--
MERGE W/ 2&> LANES	0.04	0.01	--	--	--	--	--	--	--
OFF RAMP (ALL CONTROL)									
MERGE W/ 1 LANE	0.08	0.08	--	--	--	--	--	--	--
MERGE W/ 2&> LANES	0.04	0.01	--	--	--	--	--	--	--

++ NYSDMV stopped processing most Non-Reportable accidents beginning with 2002 accident data. Therefore, the rates in Table II are based primarily on just reportable accident from NYSDMV.

Note: ACC/MEV = accidents/million entering vehicles.

FIGURE 18 New York State DOT average intersection accident rates for accident types. (*Source*: New York State DOT 2009.)

Table 18 provides dollar benefits in terms of Year 2000 dollars that may be used for benefit versus cost analysis (*Highway Economic Requirements System* 2002).

TABLE 18
AIR POLLUTION DAMAGE COSTS AND ADJUSTMENT FACTORS

Pollutant	Damage Costs $/Ton	Adjustment Factor Urban	Adjustment Factor Rural
Carbon Monoxide	100	1.0	0.5
Volatile Organic Compounds	2,750	1.5	1.0
Nitrogen Oxides	3,625	1.5	1.0

Source: Highway Economic Requirements System (2002).

Because of continuing emphasis on control of CO_2 emissions, that parameter is increasingly being used as a measure for improvements related to signal timing. The EPA (Emission Facts 2005) provides the following data:

CO_2 emissions from a gallon of gasoline = 19.4 lb/gal

CO_2 emissions from a gallon of diesel = 22.2 lb/gal

Cost and Benefit Analysis

Cost and benefit analysis is a key measure for evaluation of signal retiming. The benefit-to-cost ratio is commonly used to express the results of the analysis. Many studies have shown that signal retiming generally provides significant reductions in delay, fuel consumed, and emissions; however benefit-to-cost ratios may vary over a wide range (Skabardonis 1994; Sunkari 2004). Cost and benefit analysis has the following limitations (Papacostas 1993):

- Not all impacts considered to be important can be included in the economic analysis.
- Benefits and costs may be unevenly distributed among highway users.

Components incorporated into the cost and benefit analysis often include:

- Value of vehicle delay reduced. A dollar value for traveler time is introduced. Kruesi (1997) provides a methodology for estimating this value. Kruesi responds to the question of how to value the small time savings that often result from signal retiming projects by indicating that "the present state of knowledge does not appear to support valuing small time savings at lower hourly rates than larger savings."
- Cost of accidents reduced.
- Dollar value of reduced fuel consumption.
- Dollar value of reduced emissions.

Appendix E provides an example of a typical signal retiming evaluation methodology, as well as the benefits and costs for this case.

IN-DEPTH CASE STUDIES

All of the in-depth case study agencies reported that they performed evaluations of signal timing performance. The evaluation techniques used are shown in Table 19.

TABLE 19
SIGNAL TIMING PERFORMANCE EVALUATION TECHNIQUES USED BY AGENCIES

Evaluation Technique Used	Agencies Using Technique, $n = 7$
Travel Time Measurements	7
Intersection Observations	6
Records of Crashes	5
Simulation	3
Traffic Detectors	3

CONCLUSIONS

Most agencies evaluate the benefits of signal retiming projects. They usually do this through field observation of vehicle travel time and delay and by analyzing safety, fuel consumption, and emissions data. Simulation may be used to assist in evaluation. In recent years the following techniques have emerged to assist in data collection for retiming evaluations:

- Incorporation of evaluation capability into traffic controllers.
- Use of additional equipment in the controller cabinet, field master cabinet, and at the transportation management center to develop evaluation measures.

CHAPTER TEN

BARRIERS TO IMPLEMENTATION OF SIGNAL RETIMING PLANS

This chapter discusses the technical, institutional, and resource limitations that often result in signal retiming plans that are less effective than what is possible with the current state-of-the-art.

REVIEW OF LITERATURE

Signal Coordination Across Agency Boundaries

Coordination of traffic signals across agency boundaries is a common requirement to optimize signal timing. Timbrook et al. (2002) describe a series of in-depth case studies for which signal coordination was achieved. The study showed that coordination across agency boundaries was possible, even if the equipment and traffic system communications used by these agencies differ. The most important factor cited in the report is cooperation and communications among the agencies. In three of the in-depth case studies, the regional government agencies [metropolitan planning organizations (MPOs)] have been instrumental in bringing the agencies together and developing working plans for coordination. To successfully implement cross-jurisdictional signal timing, sometimes each of the agencies is advised to adopt less than optimal cycles or offsets to achieve the common goal of a seamless transition across neighboring boundaries. At the same time, each of the agencies wants to be able to respond to the needs of its constituents. This requires open communication between the agencies. In some cases a memorandum of understanding provides the basis for the arrangements, whereas in other cases it is done on an ad hoc basis.

Incident conditions on other facilities such as freeways provide another opportunity for signal coordination across agency boundaries. Predetermined, jointly developed timing plans to respond to incidents may be called for by a transportation management center (Carvell et al. 1996).

The 2007 *Traffic Signal Report Card* indicated that one-third of the agencies provided little to no signal coordination across agency boundaries.

Sharing of Information Devices

With the increased use of variable message signs and CCTV on surface streets, it is desirable to share the use of these devices among agencies. This is sometimes facilitated by co-location of traffic management centers or by agencies that coordinate information among operating agencies (such as TRANSCOM in the New York City metropolitan area or by the I-95 Corridor Coalition). The increasing use of the National Transportation Communications for ITS Protocol (NTCIP) standards facilitates the mobility of this type of information.

Gaps in Guidance or Tools

Some issues relating to signal timing are underemphasized either because they are not well understood or because no commonly accepted technique is available for practitioners.

Controller Option Interactions

Most of the controllers available for purchase have the features defined (as a minimum) by the NEMA TS2 standard (NEMA Standards Publication TS 2-2003 v02.06 2003). Many controllers have additional capabilities. Most of the earlier controllers commonly in use also contain many of these features. Although guidance is available for many of the parameters taken separately, because of the complexity of their interactions, it is difficult to predict their operation under certain traffic conditions (see chapter five). Although tools exist to simulate or test these interactions, many agencies do not have the resources to use these methodologies for a significant number of intersections.

Subdivision of Traffic Networks

Appendix C describes a number of analytical techniques for establishing network boundaries. Chapter three indicates that these techniques are not consistent with each other. Although agencies reported that they use such data as spacing and volume, these data are not commonly used in conjunction with analytical techniques.

Selection of the Number of Timing Plans and Their Deployment Periods

Current guidance and commonly employed practice, such as that discussed by Koonce (2008) and described in chapter three, basically depends on judgments by the analyst, and no evidence is offered to indicate that the approach leads to the best selection of plans and their deployment periods. The analytic concept described by Park et al. (2004) provides a more systematic approach, but it currently appears to be too complex for use by practitioners.

Neither method makes use of congestion-related information. It is likely that if a parameter related to congestion is introduced, the number of appropriate timing plans and their periods of use will change.

Use of Traffic Detector Data

Although most currently used traffic systems collect data from traffic detectors, it is usually not provided in formats that facilitate its use for the interpretation of timing plan performance. Prototypes for tools to address this issue appear in chapter eight, which discusses incorporating improved measures into traffic signal controllers. Chapter nine discusses the archived data user service technology, which provides improved data presentations that facilitate rapid and inexpensive feedback on system performance.

SURVEYS AND IN-DEPTH CASE STUDIES

Resource Limitations

The Puget Sound survey and the in-depth case studies indicate that resource limitations are a major barrier to improving signal retiming. The Puget Sound survey reported that 72% of the agencies interviewed had less than the desired resources.

All of the in-depth case studies conducted under this project identified resource limitations as a barrier to improved signal timing. (The in-depth case studies provide the most recent information and reflect reductions in resources imposed on some agencies by recent economic conditions.)

A somewhat different way of viewing these limitations is to consider the agency performance using the resources available to it. In the survey reported by Gordon and Braud (2009), agencies were rated on their ability to achieve objective-oriented operation (OOO). OOO roughly corresponds to a grade of 5 on the *National Traffic Signal Report Card*. Achievement of OOO was given a grade of 5.0 in Table 20 for agencies responsible for traffic signal operation.

TABLE 20
AVERAGE AGENCY SCORE RELATIVE TO ACHIEVEMENT OF OBJECTIVE-ORIENTED OPERATION

Function	Average Score (1 is lowest, 5 is highest)
Management	
Planning Documentation	2.5
Collection, Analysis, and Review of Data	2.0
Operations	
Monitoring at TOC	3.3
Personnel Qualifications	1.4
Use of CCTV	3.1
Number of Timing Plans	4.0
Frequency of Timing Plan Update	3.8
Maintenance	
Notification of Critical Failures	2.9
Time to Respond after Notification	4.5
Training and Qualifications of Maintenance Staff	3.5

Source: Gordon and Braud (2009).

Sharing of Signal Control

- Sometimes adjacent agencies may find it useful to share signal control. For example, sharing control would allow monitoring if an agency's traffic management center is not staffed on a round the clock basis. In some cases a signal may be better controlled by an adjacent agency because it is physically closer to the other signals operated by that agency and/or is more closely related to its coordination needs.

Table 21 identifies the barriers to this type of control as reported by the Puget Sound survey. Table 22 provides the survey respondents' comments on the barriers.

TABLE 21
BARRIERS TO SIGNAL CONTROL SHARING

Barrier	Percent of Agencies Identifying Barrier as an Issue
Institutional Issues	64
Technical Barriers	80
Legal/Liability	54
None Reported	10
Other (including staffing, trust, security)	20

Source: Puget Sound Regional ITS Implementation Plan (2008).

Competing Requirements

Intersection signal timing reflects the competing objectives and requirements of different classes of users. Examples include pedestrian access and safety, emergency vehicle preemption, transit priority, bicycle access and safety, interjurisdictional signal timing coordination, and neighborhood access needs. Also described are the competing requirements in descending order of importance as identified by the in-depth case studies. The in-depth case studies may not fully reflect the priorities for major cities.

TABLE 22
SURVEY RESPONDENTS' COMMENTS

City of Auburn	Personal, we're completely capable
City of Bellevue	Internal: We're understaffed, so extra work needed for interjurisdictional is low priority.
City of Marysville	Financial
City of Redmond	-If we can get communications that will allow another agency to implement certain functions, and we can maintain our own communications abilities, this is a no-brainer. -Trust that outside agency could do a better job of operating the signal. -Legal/liability: Sure, we need assurance that the other agency will secure the system and not do certain things, but that should be straightforward.
King County	The technical barriers include non-compatible controllers and central system issues. Each agency must have a work station to view and operate their signals that are connected into another jurisdiction's central system. There is a lack of true center-to-center capabilities.
Pierce County	We currently share signal timing at one interchange with WSDOT. In the past, this sharing of time of day plans has always worked well for both parties. Since the corridor affected is interconnected and operated by the County, the County informs WSDOT of the timing to be used at their interchange signals to promote progression on the corridor while minimizing queues on the ramp.

Source: Puget Sound Regional ITS Implementation Plan (2008).

COMPETING REQUIREMENTS RELATED TO SIGNAL TIMING

- **More Frequently Mentioned Conflicts**
  - Pedestrian safety and access
  - Inter-jurisdictional issues
  - Emergency vehicle preemption
- **Less Frequently Mentioned Conflicts**
  - Bicycle access at actuated phases
  - Neighborhood access
  - Transit priority

Concerning emergency vehicle preemption, Nelson and Bullock (2000) indicated that significant delays may occur when a considerable number of preemption calls are experienced.

The example of signal timing guidelines provided in Appendix B prioritizes and qualifies a number of competing objectives.

STATE OF THE PRACTICE AND CONCLUSIONS

The 2007 *Traffic Signal Report Card* (NTOC 2007) summarizes resource limitations for signal timing as follows:

> Findings from the 417 agencies that collectively account for ownership of approximately 45 percent of the nation's 272,000 traffic signals indicate that resource and management constraints limit the effectiveness of traffic signal operations. As noted throughout this report, agencies are forced into difficult choices about how to spend their limited resources. For many agencies, this simply means addressing the most critical issues on a daily basis. A proactive, integrated program management approach that includes the principles of continuous improvement, asset life-cycle costs and resource allocation for traffic signal operations is seldom seen as an option.

Specific conclusions include the following:

- Precedence graphs such as those discussed in chapter five provide a start in understanding the interaction of controller parameters. Further research should include developing priorities for parameter selection under the range of traffic demands expected at the intersection.
- Current guidance on the technique for determining network boundaries appears to be inconsistent and may be conflicting. Further research to improve guidance in this area is desirable.
- Further research on methodologies for identifying the appropriate number of timing plans and methodology to use a congestion-related measure such as occupancy would forward the state of the practice.
- Further research in developing measures for evaluating signal timing performance might include additional software in the signal controller and archived data user service technology.

CHAPTER ELEVEN

METHODS FOR INCREASING RESOURCES FOR RETIMING

Many studies have shown that retiming traffic signals provides significant benefits in terms of reduced delay, fuel consumption, and emissions, and that this technique is often underutilized. Examples of such reports include *Transportation Infrastructure* (GAO1994), and reports on the Fuel-Efficient Traffic Signal Management (FETSIM) program (Skabardonis 1994; Chien et al. 2006; Sunkari 2004). Although traffic signal equipment has improved since the earlier reports were issued, in most cases, and with the use of improved equipment and methodologies, periodic signal retiming can provide significant benefits. This chapter discusses three methods that have been used to increase awareness of the benefits of signal retiming.

RAISE AWARENESS OF BENEFITS

On the national level, the annual *Urban Mobility Report* (Schrank and Lomax 2007) points to the extensiveness of congestion and its penalties, whereas the *National Traffic Signal Report Card* (2007) describes the level of deficiencies in traffic signal timing and operation. These documents are widely reported by the press and media.

Some states have implemented publicity campaigns. An example, provided by Maze et al. (1990), is described here.

> A publicity campaign was initiated to improve the public's awareness of its receipt of restitution and possible energy savings through the signal improvements. Named "Iowa Signals Go" the campaign included a press conference, press packets sent to the media, a table-top display, a booklet, radio and television public service announcements, a 10-minute promotional videotape, newsletter articles, and discussions of the project on radio and television programs broadcast throughout the state. Programs in other states have not attempted to provide wide dissemination of information to the general public.

Some local operating agencies raise public awareness by reporting improvements to the public through signal timing. For example, Figure 19 shows the first page of a five-page report posted on the Naperville, Illinois, website (Naperville 2007).

Some agencies make a significant effort to relate benefits to public expenditures in a proactive way. The following textbox shows an excerpt from the Delaware DOT website that performs this function (Delaware DOT website 2009).

DESCRIPTION:

Traffic signal installation, upgrade, or reconstruction at nine intersections: New Castle County: SR 2 & Albertson Boulevard; US 13 & Boulden Boulevard; US 13 & Memorial Drive; US 202 & Righter Parkway; and, Mill Creek Road & McKennans Church Road. Kent County: US 13 & Lepore Road; US 13 & SR 42; and, Frederica Fire Signal. Sussex County: SR 1 & West Way Drive.

Cost:
$1.5 million.

Justification:

Improvements will improve traffic flow, vehicular safety, pedestrian safety, and the reliability of the system. Projects were initiated through a public complaint, through a study completed by our Traffic Studies Section, or through a request from our Signal Maintenance Section. Each intersection has a different scope of work, involving new signal installations, reconstruction of aging infrastructure, pedestrian signal enhancements, upgrade of curb ramps to current ADA standards, modification of left-turn phasing, and lengthening of left-turn storage bays.

The survey conducted under Gordon and Braud (2009) indicated that 29% of the agencies maintained websites to communicate the functions and/or benefits of signal timing and the role of the responsible agencies; 14% used other means of communication with the public. The in-depth case studies conducted under this project showed that relatively few agencies proactively communicate with the public.

Ogden Avenue/US Route 34 Traffic Signal System
Fort Hill Drive to Columbia Street
(4.7 Miles)
2007

TABLE 4 - TRAVEL TIME / DELAY SUMMARY

Time Period	Travel Direction	Condition	Travel Time (seconds)	Delay (seconds)	Stops	Average Speed (mph)
AM Peak	Eastbound	Before	920.0	474.3	11.7	17.2
		After	697.0	245.7	7	22.7
		Change	223.0	228.6	4.7	5.5
		% Change	24.2%	48.2%	40.2%	32.0%
	Westbound	Before	675.3	239.3	6.3	23.5
		After	568.0	168.7	3.7	27.9
		Change	107.3	70.6	2.6	4.4
		% Change	15.9%	29.5%	41.3%	18.7%
Midday	Eastbound	Before	624.0	194	6	25.4
		After	542.7	111	5	29.3
		Change	81.3	83.0	1.0	3.9
		% Change	13.0%	42.8%	16.7%	15.4%
	Westbound	Before	687.3	251	6.7	23.1
		After	552.0	152	3	28.7
		Change	135.3	99.0	3.7	5.6
		% Change	19.7%	39.4%	55.2%	24.2%
PM Peak	Eastbound	Before	732.3	293	6	21.7
		After	635.3	194.7	3.7	25
		Change	97.0	98.3	2.3	3.3
		% Change	13.2%	33.5%	38.3%	15.2%
	Westbound	Before	916.3	486.7	9.3	17.3
		After	736.0	312.7	7.3	21.6
		Change	180.3	174.0	2.0	4.3
		% Change	19.7%	35.8%	21.5%	24.9%

TABLE 5 - VEHICLE EMISSIONS SUMMARY
PERCENT REDUCTION

Time Period	Travel Direction	Hydrocarbons (grams/day)	Carbon Monoxide (grams/day)	Nitrogen Oxide (grams/day)
AM Peak	Eastbound	7%	2%	-11%
	Westbound	5%	-5%	-1%
Midday	Eastbound	5%	2%	-2%
	Westbound	13%	1%	12%
PM Peak	Eastbound	9%	8%	5%
	Westbound	10%	2%	3%

TABLE 6 - VEHICLE EMISSIONS SUMMARY
ANNUAL EMISSION REDUCTION

Time Period	Hydrocarbons (tons/year)	Carbon Monoxide (tons/year)	Nitrogen Oxide (tons/year)
AM Peak	-16	10	10
Midday	-40	-71	-13
PM Peak	-28	-140	-6

FIGURE 19 Comparison of before and after timing performance. (*Source*: Naperville 2007.)

RESPOND TO FEEDBACK FROM THE PUBLIC

Public support for increased resources for signal timing may be enhanced if the agency is perceived to be responsive to the public's comments and complaints. Gordon and Braud (2009) indicated that 29% of the agencies conduct surveys and that 43% of the agencies have easy telephone access for this purpose.

COOPERATE WITH OTHER AGENCIES

In some cases agencies have found it expedient to cooperate to facilitate the planning and budgeting process. Cooperation may include traffic engineering technical assistance programs, shared databases, and regional databases. Estrella and Georgevich (2000) and Carvell et al. (1996) provide examples of this. MPOs sometimes take the lead in initiating budgeting for traffic signal programs. Figure 20 (SPC 2009) shows the cover letter for a solicitation from an MPO for traffic signal projects.

Southwestern Pennsylvania Commission

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Armstrong County
James V. Scahill
Beaver County
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Butler County
James L. Kennedy
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Luke Ravenstahl
Fayette County
Vincent Zapotosky
Greene County
Pam Snyder
Indiana County
Rodney Ruddock
Lawrence County
Steve Craig
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Jake Wheatley
Governor's Office
Allen Kukovich
PA Dept. of Transportation
James D. Ritzman
PA Dept. of Community and Economic Development
Jack Machek
Executive Director
James R. Hassinger

August 27, 2008

To: Local Governments in the SPC Region

Subject: Request for Projects-Regional Traffic Signal Program, 2009 Cycle

The Southwestern Pennsylvania Commission (SPC) is pleased to invite your agency to submit applications for the first cycle of the Regional Traffic Signal Program. Successful applicants will receive assistance with traffic signal retiming and other improvements that will result in optimized operations. There are two types of traffic signal projects that are included in the program:

1) Signals In Coordination or "SINC" projects involve work which results in implementation of new timing and coordination plans for signals that are properly equipped; and

2) Signals In Coordination with Equipment Upgrades or "SINC-UP" projects involve work which results in upgrading traffic signal equipment that has a direct impact on optimized operations as well as implementation of new timing and coordination plans.

The Program Guidelines and Application Instructions document is attached (October 17, 2008 submission deadline). This document as well as the applications for the program can be downloaded from SPC's website:

http://www.spcregion.org/trans_ops_traff_rtsp.shtml

SPC appreciates your interest in this solicitation and looks forward to receiving your applications. Please feel free to contact Domenic D'Andrea with any questions (412-391-5590 ext. 341).

Sincerely,

Chuck DiPietro

Charles M. DiPietro
Transportation Planning Director

Attachment

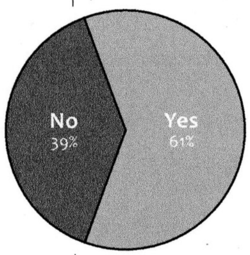
The Metropolitan Planning Organization and Local Development District

FIGURE 20 Cover page for solicitation for traffic signal projects. (*Source*: SPC 2009.)

Agencies in a region may share skills, experience, and training on either a formal or informal basis. Figure 21 provides responses to the Puget Sound survey that addressed this issue.

25. Are there any special skills or training that your staff has, that you might be willing to share with other agencies through a regional "knowledge pool"? If yes, please describe:

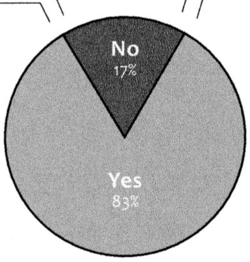
City of Federal Way
City of Issaquah
City of Kirkland
City of Marysville
City of Renton
City of Seattle/SDOT
Pierce County



City of Auburn	*Fiber networking of signals, communication, use of encoders and cameras.*
City of Bellevue	*Traffic responsive setup issues, communication systems, controller expertise, TMC operations, etc*
City of Edmonds	*Coordination*
City of Everett	*City has an experienced signal designer*
City of Kent	*Signal timing/coordination plan development, system integration, special applications for video surveillance, communications network*
City of Lynnwood	*Installation of over 450 video detection cameras, customized pinouts for the signal cabinets, UPS installations, 3M opticom coding and lockouts, temperature probes, creating links from planning to analysis to operations using software, fiber design and splicing, modem configuration and data transmission*
City of Redmond	*Knowledge in IT (Systems administration), fiber cable maintenance, video detection setup, loop detector placement, isolated signal timings.*
King County	*Signal operations, ITS Expertise, ITS Project Management and Design, synchro expertise, econolite/eagle/TS2 expertise, video compression techniques, video transmission over various communications media.*
Snohomish County	*Anything we can*
WSDOT NW Region	*We would be willing to share any knowledge that would assist in regional signal operations*
WSDOT Olympic Region	*TRACONEX TMP 390 operations*

26. Are there any skills development or training opportunities that would be particularly valuable to your agency that you would like to have provided by a regional knowledge pool or other experts?

City of Edmonds
City of Marysville
Pierce County



City of Auburn	*Traffic data collection, volume and flow maps, VMS experience, equipment specifications*
City of Bellevue	*TSP operational strategies, LRT operational strategies, adaptive strategies*
City of Everett	*Fiber optic communication, CCTV, and advanced signal controller operation and maintenance*
City of Federal Way	*Convincing Council to adequately fund operations*
City of Issaquah	*ACTRA Training*
City of Kent	*Regional signal system coordination, network access security protocols, data acquisition & management system, information dispersion (via internet) such as flow maps/real-time traffic conditions, regional emergency management planning*
City of Kirkland	*ITS equipment maintenance*
City of Lynnwood	*DMS signs with graphical display*
City of Redmond	*battery backup operations and maintenance, fiber optic cable documentation, communications design and troubleshooting, data management, inventory*
City of Renton	*Fiber optic cable installation and maintenance*
City of Seattle/SDOT	*Network Arch., traffic resposive, license plate reader (travel time), DMS*
King County	*Center to center, NTCIP, VMS, networking, router programming*
Snohomish County	*Fiber optics information*
WSDOT NW Region	*Any knowledge that would help with future signal operations, maintenance, and policy*
WSDOT Olympic Region	*Any training that is available relating to traffic signal or ITS maintenance and operations*

FIGURE 21 Assistance sharing. (*Source*: Puget Sound Regional ITS Implementation Plan 2008.)

CHAPTER TWELVE

CONCLUSIONS

This synthesis of research examined the following:

- Signal timing policy, management, and planning
- Network treatments
- General signal timing and retiming considerations
- Requirements for signal timing
- Use of retiming methodologies and personnel qualifications
- Methodologies for field implementation of timing plans
- Personnel resources and cost for implementation of signal timing plans
- Performance measures
- Evaluation of signal timing performance
- Barriers to implementation of signal retiming plans
- Increasing resources for retiming

The synthesis concluded that although modern traffic controllers are complex and contain many options, traffic engineers in responsible charge were generally knowledgeable in their use. They generally emphasize pedestrian and vehicle safety as well as bandwidth maximization in preference to signal timing strategies that minimize vehicle delay. They are generally sensitive to a variety of competing needs for green time and respond appropriately. Respondents to several surveys cited lack of resources as the key obstacle to improved signal timing.

The literature, surveys, and in-depth case studies indicate the following:

- Resource limitations are the most significant factor contributing to suboptimal signal retiming.
- Most traffic engineers understand that competing priorities among users and modes require servicing of all needs, with pedestrian and vehicle safety being the primary requirements. Although review and retiming of traffic signals at intervals of 30 months to 3 years is advised, most agencies exceed this interval somewhat but perform retiming within 5 years. Signal retiming may be conducted at periodic intervals or may be initiated as the result of such triggers as land use changes or observed changes in congestion patterns. In some cases detector data may indicate volume changes. There is little guidance for the use of detector data to systematically identify the need for retiming.
- Currently used traffic controllers contain many signal timing parameters and options, and considerable guidance exists for setting most of the parameters. Although the parameters, taken individually, are well understood by traffic engineers in responsible charge, because of their complexity it is sometimes difficult to anticipate how they will interact with each other. The available tools do not indicate how these parameters may be best collectively adjusted to improve performance with no adverse impact on safety.
- The development of timing plans for signal coordination is generally well understood by traffic engineers, and the tools to support this development are generally well suited to the task. Although several methodologies to define the boundaries of the sections to be coordinated are available, they sometimes conflict. These methodologies appear to be underutilized by traffic engineers.
- There is little useful guidance for the identification of the number of timing plans that may be effectively used, and the time periods for which deployment is appropriate. As a result, traffic engineers use techniques based on experience and a general review of volume profiles. Research to develop guidance based on volume, occupancy, and intersection saturation is appropriate.
- The existing guidance to establish the type of signal control (pretimed, semi-actuated, fully actuated) as a function of traffic conditions is limited. Current guidance to establish the conditions for the use of fully actuated controllers under coordinated conditions is insufficient. Guidance for the use of volume-density operation is also insufficient.
- The cost of signal retiming is $3,700 or less per signal for most agencies.

Although most of the coordinated traffic systems in the United States operate on a time-of-day basis, alternatives exist for coordinated systems to respond to changing traffic conditions.

- *Conventional traffic responsive systems*. These systems employ a relatively small number of system detectors. Although research has shown that these conventional systems are beneficial under some traffic conditions, little guidance is available for when this type of operation is best employed. In some cases, it is difficult to identify threshold parameters for the detector settings to be used for selecting timing plans. In other cases it is difficult to migrate timing plans into corresponding controller selection settings. These difficulties appear to discourage the use of conventional traffic responsive operation.

- *Traffic adaptive systems*. A number of traffic adaptive systems have been installed in the United States. Most of the agencies using these systems found performance to be generally improved and reported a higher level of improvement for operation in oversaturated conditions. Although they generally avoid the problems with traffic conventional responsive systems cited earlier, traffic adaptive systems are expensive, require a large number of detectors, and generally do not support equipment interchangeability among suppliers.

Most agencies take considerable care in physically implementing timing plans in field controllers and checking to ensure that they are properly installed and functioning. Similarly, agencies generally expend considerable resources in fine-tuning timing plans and evaluating their performance.

Performance evaluations often involve a labor-intensive process. Archived Data User Service (ADUS) coupled with Archived Data Management Systems (ADMS) technology is an emerging approach that may reduce the labor-intensive characteristics of evaluations and provide a basis for identifying retiming needs.

Further research to address these gaps includes the following:

1. Better understanding of the interactions of controller timing plan parameters may include hardware-in-the-loop capabilities.

2. Improved methodologies to establish the boundaries of coordinated traffic networks (sections) and to select intersections for isolated operation within or near coordinated networks.

3. Research on the number of timing plans that are appropriate, the best periods of operation, and the most appropriate timing plan transition techniques. This research would examine processes to use data developed by system traffic detectors to develop operational profiles for such traffic scenarios as weekdays, weekends, holidays, and special events.

4. Research related to Item 3 resulting in guidance to practitioners can be used to establish the appropriate type of signal control (pretimed, semi-actuated, fully actuated) as a function of traffic conditions. Guidance would also be useful to establish traffic conditions for the use of fully actuated control with signal coordination and for the appropriate use of volume-density operation.

5. As discussed in chapter five, recent research highlights a strong relationship between detection zone length and passage time settings. Additional research would enhance understanding of this relationship.

6. Chapter five indicates that the use of very long cycle lengths at isolated intersections is extensive and may be counter-productive. Research to further develop an understanding of this relationship would be useful.

7. Because of its labor-intensive character, evaluation of system performance, although extremely important, is expensive as currently practiced. A more automated capability would not only reduce evaluation costs per se, but will also go far toward identifying when retiming is warranted. Although ADUS coupled with ADMS provides the general structure for data analysis, relatively few implementations have been developed for signal systems, and these are not marketed in a convenient form for agencies to use. Similarly, some controllers have incorporated software that enhances the capability to provide measures that are useful for signal timing evaluation. Research would be useful to review existing work to date, and to develop the design requirements for a cost-effective approach that may be widely deployed to provide common evaluation parameters such as delay.

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GLOSSARY

Accident modification factors—A means of quantifying crash reductions associated with safety improvements.

Actuated signal control—Timing intervals are called and extended in response to vehicle detections.

Bandwidth—The maximum amount of green time for a designated direction as it passes through a corridor at an assumed constant speed, typically measured in seconds.

Bluetooth—An open wireless protocol for exchanging data over short distances.

Centrally controlled system—A system that provides signals to the intersection traffic controller to directly control each phase or each interval of the signal cycle.

Clearance time—The time in seconds between signal phases to transition between normally conflicting movements.

Closed loop system—A three-level distributed signal control system. It includes a central computer, field master controllers, and local controllers. Timing plans may be downloaded to field controllers and supervised at the central site.

Controller or field controller—The devices that operate traffic signals by controlling the sequence and duration of the indications displayed.

Coordination—The ability to synchronize multiple intersections to enhance the traffic flow of one or more directional movements in a system.

Crash reduction factors—See "accident modification factors."

Cycle length—The time needed for a complete sequence of signal indications.

Detection mode—Detectors may operate in the presence mode (continuous detection of vehicles within the sensing field of the detector) or the passage mode (detector indicates a pulse).

Fine tuning—Adjustments to the basic signal retiming settings made by observing the interaction of vehicles with the timing parameters.

Fully actuated signal—Signal timing on all approaches is determined by traffic actuation.

GPS—Global Positioning System.

Green band—The width of the band (in seconds) that indicates the amount of green time that traffic can flow with a selected speed through a number of coordinated intersections.

Interval—The time duration when traffic signal indications do not change. An actuated traffic signal controller also has timing intervals (minimum green, passage time) that determine the length of the green interval.

Isolated intersection—An intersection whose approach traffic flow is not significantly influenced by the signal timing of upstream intersections; that is, vehicles do not arrive at the intersection in platoons. Isolated intersections (intersections that are not coordinated with adjacent intersections) may be present within a network because they operate more effectively under certain conditions such as oversaturation.

Level of service—Defined in terms of control delay. Control delay is the total elapsed time from when a vehicle joins a queue until it departs from the stopped position at the head of the queue.

Maximum green (time)—The maximum length of time that a phase can be green in the presence of a conflicting call.

Minimum green (time)—The shortest time for which the green indication will be given to the approach or approaches.

MUTCD—Manual on Uniform Traffic Control Devices.

Network—A set of signals whose signal timing is coordinated. Sometimes called a *section* the signals operate in the same control mode (e.g., time of day). New signal timing plans are provided to all signals in the section simultaneously.

NEMA—National Electrical Manufacturers Association.

NTCIP—National Transportation Communications for ITS Protocol.

Offset—The time relationship between a defined point in the green interval (such as the start of green) and a defined master clock reference.

Passage time—See vehicle extension time.

PDA—Personal digital assistant.

Pedestrian walk—A signal indication that allows pedestrians to begin to cross an intersection.

Phase—A set of signal displays that control a specific combination of vehicular and pedestrian movements.

Preemption—The transfer of normal operation of a traffic control signal to a special control mode of operation that facilitates the passage of trains and emergency vehicles by prohibiting conflicting operation of normal traffic flows.

Progression—Coordination of traffic signal timings that results in a high proportion of vehicles arriving during the green period (good signal progression) while traveling from one signal to the next.

Red clearance—A clearance interval that may follow the yellow interval during which the terminating phase and all other phases display red.

Ring—Set of phases that may operate one after another. A ring and barrier diagram is often used to depict these relationships.

Saturation—The traffic flow condition when demand equals or exceeds capacity. When demand exceeds capacity it is sometimes called oversaturation.

Section—See "network."

Semi-actuated signal—Signal for which timing on one or more, but not on all, approaches is determined by traffic actuation.

Spillback—Condition in which a queue from a downstream intersection uses up all the space on a link and prevents vehicles from entering the upstream intersection on the green.

Split —The time assigned to a phase (the greater of the green and yellow plus all red or the pedestrian walk and clearance times) during coordinated operation; may be expressed in seconds or percent of cycle.

Traffic adaptive control—Real-time implementation of signal timing plans for a network. Implementation periods may be on a cyclic basis or may be changed within a cycle. In addition, changes may be introduced based on measurements made over several cycles.

Traffic management center (TMC) or traffic operations center (TOC)—A central control facility used to manage traffic signal systems. It may be combined with other traffic management functions such as freeway management systems or police operations management facilities.

Traffic-responsive control—Selection of stored timing plans based on measurements of current traffic conditions. Volume and occupancy are the most commonly used measurements.

TMC—Transportation management center or traffic management center.

Vehicle green—The duration of the green indication for a given movement.

Vehicle extension time—A preset time interval extending the green time for each vehicle detection in an actuated controller. It may be reduced using the volume-density features of a controller.

Volume-density control—A form of actuated control in which the initial green interval and the vehicle extension interval are varied as a function of traffic conditions and time.

Volume-to-capacity ratio—The ratio of the volume approaching an intersection to the approach capacity.

Wireline—Transmission of signals using a physical form of interconnection cable such as copper cable or fiber optic cable.

APPENDIX A

IN-DEPTH CASE STUDIES

The synthesis employed the results of four surveys conducted under the following projects, as well as a set of case studies performed under this project.

- *National Traffic Signal Report Card* (National Transportation Operations Coalition 2007)
- *Puget Sound Regional ITS Implementation Plan* (Puget Sound Regional Council et al. 2008)
- *Signal Timing Practices and Procedures* (Tarnoff and Ordonez 2004)
- *Traffic Signal Operations and Maintenance Staffing Guidelines* (Gordon and Braud 2009)

The case studies conducted under this project were intended to obtain in-depth information on traffic signal timing practices. Thus the questionnaire not only solicited statistical information, but also provided an opportunity for the type of anecdotal information leading to a better understanding of the reasons for the choice of practices. Follow-up questions resulted in additional information.

Seventeen case study solicitations resulted in seven in-depth responses. Two agencies provided documents that they had developed, and this material was incorporated into the synthesis.

Some responses to the questionnaire suggested the following set of follow-up questions to some of the participating agencies:

- How did you select the sections for traffic responsive operation?
- How do you establish the boundaries for the networks (sections) for your coordination plans?
- How did you select the intersections to be placed on the SCATS system?

Requests for additional information resulted in Figure 19 in chapter 11 and Appendix B.

Table A1 provides a summary of the responses to the case study questionnaire.

TABLE A1
SUMMARY OF CASE STUDY RESPONSES

	Agency						
	a	b	c	d	e	f	g
Case Study Question							
1.2 Number of signals	535	90	720	1,300	151	850	3,000
a. Coordinated	403	87	360	1,270	148	775	2,250
b. Isolated	172	3		30	3	75	750
1.3 Type of Coordination							
a. Closed loop	Yes	Yes	Yes			Yes	Yes
b. Central	Yes			Yes	Yes		Yes
c. Adaptive	Yes			Yes			
d. Time base	Yes	Yes		Yes	Yes		Yes
e. Other							
2 Management							
2.1 Agency procedures for							
a. TMC Operating Procedures	Yes	NA	Yes	No	Yes	No	No
b. Maintaining traffic signals	Yes	Yes	Yes	Yes	Yes	Yes	Yes
c. Retiming signals	Yes	No	Yes	IP	Yes	Yes	No
2.2 Compatibility with Regional Architecture and Standards	Yes		NTCIP	Yes	Yes	Yes	No NTCIP
2.3 Documentation	Yes	Yes	Yes	No	Yes	No	No
2.4 Review periods for operations and performance							
a. 1 year or less						Yes	
b. 1 to 2 years		Yes					
c. 2 to 3 years	Yes						
d. 3 to 5 years			Yes		Yes		Yes
e. Over 5 years or not reviewed				Yes			
2.5 Intervals for phasing review	3	No defined	As needed	Note 1	5–10 yrs	N	As needed
2.6 Intervals for geometrics review	3	No defined	As needed	Note 1		N	As needed
2.7 Retiming after geometric models	Yes	Yes	As needed	Yes	Yes	Yes	Yes
2.8 Objectives							
a. Documented objective for signal timing	No	No	Yes	No	Yes	Yes	Yes
b. Describe objectives							
c. Describe conflicts							
d. Vehicle classes for preempt	F	PFA	FA	F	F	FA	FAP

TABLE A1 continues on next page

TABLE A1 continued

	Agency						
	a	b	c	d	e	f	g
e. ICM or interagency coordination objectives	Yes	Yes	Yes	Yes	Yes	Yes	NA
2.9 % signals employing preempt	70	100	25	6	60	15	75
3. Basis for retiming							
3.1 Need for retiming							
a. All signal at periodic intervals			1	1		1	
b. Periodic using priority structure or roadway type	1		1		1		1
c. Field or CCTV observations	1	1	1		1	1	1
d. Detectors					1	1	1
e. How analyze data							
f. Other triggers		Note 4	1	1			1
g. Other						1	1
3.2 Average retiming interval							
a. 1 year or less							
b. 1 to 2 years							
c. 2 to 3 years						Yes	
d. 3 to 5 years	Yes	Yes	Yes		Yes		Yes
e. Over 5 years				Yes			
3.3 Does timing vary by street class	Yes	Yes	Yes	No	Yes	Yes	No
3.4 If 3.3 positive explain approach							
3.5 Approach for rephasing							
a. Critical lane anal	Yes				Yes		Yes
b. Separation of conflicting movements.	Yes	Yes					Yes
c. Volume warrants	Yes	Yes	Yes	Yes	Yes		Yes
d. Pedestrian conflicts	Yes	Yes			Yes	Yes	Yes
e. Collision analysis	Yes	Yes	Yes	Yes	Yes	Yes	Yes
f. Consistency					Yes		Yes
g. Green band					Yes	Yes	Yes
h. Left turn observations		Yes		Yes	Yes	Yes	Yes
I. Other							
3.6 Number weekday timing plans	3	4	4	3-4	7	5	3-5
3.7 Other timing plans							
a. Incidents	No	No	Yes		Yes	Yes	Yes
b. Saturdays	Yes	Yes	Yes	Yes	Yes	Yes	Yes

TABLE A1 continues on next page

TABLE A1 continued

	Agency						
	a	b	c	d	e	f	g
c. Sundays	Yes	Yes	Yes	Yes	Yes	Yes	Yes
d. Holidays		Yes	Yes	Yes	Yes	Yes	Yes
e. Weather					Yes		
f. Special events	Yes		Yes	Yes	Yes	Yes	Yes
g. Other				Note 2			
3.8 Total non-weekday plans	1	0-4	1-5	1-2	4-6	2-3	1-3
3.9 How determine time periods		V, O		V	S, O	V	Note 3
3.11 Use ACS Lite	No	No	No	No	No	No	No
3.12 Use traffic responsive	NA	No	No	NA	Yes	Yes	Yes
3.13 Data for signal retiming							
a. Turning movements	Yes	Yes	Yes	Yes	Yes	Yes	Yes
b. ATC					Yes		Yes
c. Traffic system data							Yes
d. Travel time/delay		Yes	Yes		Yes	Yes	Yes
e. Other							
3.14 Pedestrian detectors	Yes	No	Yes	No	Yes	Yes	Yes
3.15 Current walking speed	3.5-4	3.5-4	3	4	3.5	3.5-4	3-4
3.16 Future walking speed	3.5	3-4	3	3.5	3.5	3-3.5	3-3.5
3.17 Neighborhood traffic mgt.	No	No	No	No	Yes	No	No
4 Retiming tools and personnel qualifications							
4.2 Personnel qualifications person in charge of timing							
a. PE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
b. PTOE		Yes			Yes	Yes	
c. TSOS							
d. TOPS							
e. Courses		Yes	Yes	Yes	Yes	Yes	Yes
f. Training suppliers		Yes	Yes	Yes	Yes	Yes	
g. Years of experience	21	8		15	24		
h. Other							
5 Field implementation							
5.1 Method							
a. Central control							Yes
b. Download from central computer			Yes		Yes	Yes	

TABLE A1 continues on next page

TABLE A1 continued

	Agency						
	a	b	c	d	e	f	g
c. Download from laptop or desktop	Yes		Yes	Yes		Yes	Yes
d. Manually insert		Yes	Yes	Yes			Yes
e. Other							
5.2 Insurance of timing plans							
a. Computer checks only		Yes?					
b. Verify in field	Yes	Yes	Yes	Yes	Yes	Yes	Yes
c. Other							
5.3 Fine tune							
a. Do not fine tune							
b. Observe field parameters	Yes	Yes	Yes	Yes	Yes	Yes	1
c. CCTV			Yes	Yes	Yes	Yes	
d. Simulation					Yes		Yes
e. Detector data					Yes		Yes
f. Other							
g. Controller drift check needed		Yes		Yes	Isolated		Isolated
6 Resources							
7.1 Performance measures for retiming							
a. Delay	Yes	Yes	Yes	Yes	Yes	Yes	Yes
b. Stops	Yes	Yes	Yes	Yes	Yes	Yes	Yes
c. Emissions and fuel		Yes			Yes	Yes	Yes
d. Bandwidth maximization	Yes	Yes	Yes		Yes	Yes	Yes
e. Variation in trip time or delay	Yes	Yes			Yes	Yes	Yes
f. Other							
7.2 Strategies for saturation							
a. Balance delays	Yes	Yes				Yes	Yes
b. Manage queues		Yes	Yes		Yes	Yes	Yes
c. Suspend coordination					Yes	Yes	Yes
d. Other			Yes				
8 Evaluation of performance							
8.1 Do you evaluate	Yes	Yes	Yes	Yes	Yes	Yes	Yes
8.2 Evaluation techniques used							
a. Travel time measurements	Yes	Yes	Yes	Yes	Yes	Yes	Yes
b. Intersection observations		Yes	Yes	Yes	Yes	Yes	Yes

TABLE A1 continues on next page

TABLE A1 continued

	Agency						
	a	b	c	d	e	f	g
c. Accident records		Yes		Yes	Yes	Yes	Yes
d. Simulation			Yes	Yes	Yes		
e. Traffic detectors				Yes	Yes		Yes
f. Other							
8.3 Evaluation measures							
a. Delay		Yes	Yes	Yes	Yes	Yes	Yes
b. Stops		Yes	Yes	Yes	Yes	Yes	Yes
c. Accidents		Yes		Yes	Yes	Yes	Yes
d. Route travel time	Yes	Yes	Yes		Yes	Yes	Yes
e. Reliability of travel time			Yes		Yes		
f. Emissions and fuel		Yes			Yes	Yes	Yes
g. Other							

Notes for Response Table

1. Annually and when requested by a supervisory agency.
2. School start and end times.
3. By review of capacity analysis, hourly through and turning movement counts, and specific detector volumes and occupancies. Systems are then set with TRP plans and fine tuned and observed until optimized. Consultants doing this work are required to retime should the system break down within 5 years unless due to significant changes in access, geometry, or infrastructure.
4. New signals, major development or land use changes, geometric changes, major shifts in patterns.

CASE STUDY QUESTIONNAIRE

NCHRP SYNTHESIS PROJECT 20-05
TOPIC 40-10
TRAFFIC SIGNAL RETIMING PRACTICES IN THE UNITED STATES

The Transportation Research Board's National Cooperative Highway Research Program has commissioned a study on traffic signal retiming practices in the U.S. The goal of the research is to identify and provide information to practitioners regarding the techniques and resources appropriate for signal timing, to provide information on competing stakeholder objectives and to identify barriers to providing effective signal timing and the methods to overcome the barriers. As someone with experience in this area, we would appreciate your input on the subject.

Please be assured that your responses will be kept in strictest confidence, to be aggregated with all other responses.

1. General

1.1 Name of agency and type (city, county, state)

1.2 Number of signals

a. Coordinated signals ______________________________

b. Isolated signals ______________________________

1.3 What type of system coordination do you use (check all that apply):

c. Closed loop (pretimed and/or traffic responsive) ______________

d. Central (pretimed and/or traffic responsive second-to-second control provided by central computer)______________

e. Adaptive______________________________

f. Time base coordination ______________________________

g. Other (please explain) ______________________________

2. Management

2.1 Does your agency have documented procedures for:

a. Traffic Management Center operating procedures ______________

b. Maintaining traffic signals______________________________

c. Retiming traffic signals ______________________________

2.2 Is your traffic system compatible with the regional ITS architecture data flows and the standards that support them ______________________________

2.3 Do you have a document that describes plans for capital and operational upgrades and for the implementation of signal retiming______________________________

2.4 At which periods are signal operations and performance measures reviewed for the need for retiming and rephrasing ______________________________

a. One year or less ______________________________

b. One to two years ______________________________

c. Two to three years ______________________________

d. Three to five years ______________________________

e. Greater than 5 years or not reviewed ______________________

2.5 At which intervals (if any) do you periodically review phasing ______________

2.6 At which intervals (if any) do you periodically review the need for geometric modifications__________________

2.7 Do you retime signals after performing geometric modifications_____________

2.8 Objectives

a. Does your agency have documented objectives relating to signal timing____

b. If the response to 2.8.a above is positive please describe objectives or enclose documentation.

c. Please describe conflicts in objectives which your agency has experienced in providing traffic flow efficiency with such other possible objectives as safety issues, bicycle safety and mobility, transit priority, emergency vehicle preempt, pedestrian issues, cross jurisdictional coordination, and neighborhood traffic management.

d. If emergency vehicle preempt is provided, please identify the vehicle classes for which preempt is employed.

e. Are Integrated Corridor Management (ICM) and/or inter-agency signal coordination among your agency's objectives ____

2.9 What percentage of your signals employ emergency vehicle preempt ________

3. Basis for Signal Retiming

3.1 How do you establish the need for retiming (check all that apply):

a. Retime all signals at periodic intervals ________________________________

b. Retime at periodic intervals using a priority structure or roadway type ____

c. Review of field observations or CCTV observations ____________________

d. Review of traffic detector data_______________________________________

e. If 3.1.d above is positive please explain how you analyze the data.

f. f.Other triggers (e.g., new traffic signals in area, new development, geometric changes)

g. Other (please explain):

3.2 What is the average retiming interval employed by your agency

a. 1 year or less____

b. From 1 to 2 years ____

c. From 2 to 3 years ____

d. From 3 to 5 years ____

e. Greater than 5 years ____

3.3 Does the retiming interval vary by street classification ____________________

3.4 If the response to 3.3 is positive, please explain your usual approach to this issue

3.5 Which techniques are employed for rephasing

a. Critical lane analysis ____

b. Maximum separation of conflicting movements________________________

c. Volume warrants ____

d. Avoidance of pedestrian conflicts ____________________________________

e. Collision analysis ____

f. Retention of consistency (e.g., avoidance of phase changes as a function of time of day or timing plan) to avoid motorist confusion ____

g. Green band emphasis ____

h. Observing intersection during peaks for adequacy of left turn treatment ____

i. Other (please explain):

3.6 How many normal weekday timing plans do you employ_____

3.7 Which other timing plans do you provide (check all that apply):

a. Incidents (special plan for diversion during incidents) ___________________

b. Saturdays ____

c. Sundays ____

d. Holidays ____

e. Weather (plans for snow or fog or other weather related effects) ___________

f. Special events ____

g. Other (please explain):

3.8 What is the total range in the number of non-weekday timing plans that your agency usually employs_________________

3.9 How are the time periods for normal weekday plans determined (please explain):

____

3.10 Please identify systems, if any, used for adaptive operation (e.g. SCOOT, SCATS, RHODES, RT-TRACS, other)

3.11 Do you use ACS Lite _______________________

3.12 Do you use system traffic responsive operation as provided by closed loop or central control (second by second control) systems. If so please explain the basis for establishing plan selection parameters.

3.13 Which of the following data do you use for data for signal retiming (check all that apply):

a. Turning movement counts ____

b. Automatic traffic counters (if used, explain how used)___________________

c. Data collected by traffic system (if used, explain how used) ______________

d. Travel time/delay studies ____

e. Other (if used, explain how used):

3.14 Do you use pedestrian detectors ______________

3.15 What walking speed is currently used for signal timing ___________________

3.16 What walking speed will be used in the future for signal timing_____________

3.17 Do you employ signal timing or phasing policies that limit traffic access to designated areas or provide neighborhood traffic management_____________

4. Retiming Tools and Personnel Qualifications

4.1 Which of the following retiming tools do you use:

4.1.1 Optimization

a. SYNCHRO ____________________

b. TRANSYT 7F ____________________

c. Passer II ____________________

d. Passer III ____________________

e. Passer IV ____________________

f. Manual time-space diagrams____________________

g. Other (please explain):____________________

4.1.2 Which of the following simulation techniques do you use:

a. CORSIM ____________________

b. SimTraffic ____________________

c. Other (please identify): ____________________

4.1.3 Which other techniques do you use:

a. Highway capacity software ____________________

b. Other (please explain):____________________

4.1.4 Personnel qualifications—Please identify the qualifications and experience for the person(s) in charge of signal retiming:

a. PE____________________

b. Professional Traffic Operations Engineer (PTOE) ____________________

c. Traffic Operations Signal Specialist (TSOS)____________________

d. Traffic Operations Practitioner Specialist (TOPS) ____________________

e. Courses in traffic engineering ____________________

f. Training courses provided by software suppliers ____________________

g. Years of experience in signal retiming (please provide) ____________________

h. Other (please explain):____________________

5. Field Implementation of Timing Plans

5.1 What is the principal method used to implement timing plans in the field controller

a. Use central control (second by second control) that times the signals for non-clearance intervals directly from the central computer ____________________

b. Download from a central computer____________________

c. Download from a laptop or desktop computer ____________________

d. Manually insert timing plans into field controller____________________

e. Other (please explain):____________________

5.2 How do you insure that the plans delivered by the field controller are identical to those that were developed and proposed for use:

a. Only use computer based checks (no field verification) ________________

b. Verify all plans using field observations ____________________________

c. Other (please identify): ____

5.3 How do you fine tune timing plans

a. Do not fine tune ____

b. Observe such field parameters as spillback from turning bays, slack time, spillback to upstream intersection and make adjustments accordingly ______________________________

c. Conduct observations such as in 5.3b by CCTV ______________________

d. Use of simulation models ____

e. Use of measures based on detector data ______________________________

f. Other (please explain):____

5.4 Is it necessary to check internal controller clock drift_____________________

6. Resources Appropriate for Retiming

Agencies may perform some or all of the retiming tasks themselves or contract some or all of the tasks. The following is intended to identify the costs or time estimates for retiming on a per intersection basis. It may be more convenient for respondents to provide a total for each column rather than the components in the table.

Task	If performed with own staff		If contracted
	Engineering hours	Technician hours	$
Selection of intersections for retiming			
Data collection			
Timing optimization including any office simulation for fine tuning			
Establishing timing plans in controller, field checking and field fine tuning			
After studies and report preparation			
Total			

Any other relevant resource information ______________________________

7. Performance Measures for Timing Signals

7.1 Which measures do you use for retiming signals (check all that apply):

a. Delay ____

b. Stops____

c. Emissions and fuel consumption______________________________

d. Arterial bandwidth maximization______________________________

e. Variation in trip time or delay ______________________________

f. Other (please explain) ____________________

7.2 Please identify the following which you use for timing of saturated phases or saturated intersections:

a. Balance delays on all approaches____________________

b. Manage queues ____________________

c. Suspend coordination and use alternative strategy ____________________

d. Other (please explain):____________________

8. Evaluation of Signal Timing Performance

8.1 Does your agency perform evaluations of signal performance____________________

8.2 If your agency evaluates signal performance please identify the following techniques used:

a. Vehicle travel time measurements____________________

b. Intersection observations of queues, delay, saturation, etc. ____________________

c. Review of accident records ____________________

d. Simulation ____________________

e. Measures provided by traffic system detectors ____________________

f. Other (please explain): ____________________

8.3 Measures used for evaluation of field performance (please check all that apply):

a. Delay ____________________

b. Stops____________________

c. Accidents ____________________

d. Route travel time ____________________

e. Reliability of travel time ____________________

f. Emissions and fuel consumption____________________

g. Other (please explain):____________________

9. Management Issues

9.1 Please identify and comment on potential barriers to implementing improved signal timing performance that your agency may have experienced. Examples may include funding limitations, staffing/time limitations, lack of adequate tools or excessive complexity of tools, conflicting objectives.

____

9.2 Please identify and comment on activities that your agency may have undertaken to improve the resources available for signal timing. These may include raising public awareness or awareness on the part of decision makers on the efficiencies to be obtained through improved timing, encouraging public feedback, publicizing other reports such as FHWA and RITA reports on the effect of improvements.

____

Thank you for completing this survey. Your responses will help provide insights into how to improve signal timing practices. If you have any questions regarding the survey, please contact Bob Gordon, rob.gordon3@verizon.net, (516)938-2498. If you have documentation that might be helpful it can be mailed to:

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Dunn Engineering Associates
36 Stauber Drive
Plainview, N.Y. 11803

APPENDIX B

SIGNAL TIMING POLICIES, GUIDELINES, AND STRATEGIES

The following document, provided by Mr. Thomas Soyk of the City of White Plains, N.Y., illustrates the development of signal timing policies, guidelines, and strategies.

SIGNAL TIMING GUIDELINES—CITY OF WHITE PLAINS, NEW YORK

General

The primary objective in the timing of signals is often considered to be overall safety. There is particular concern for pedestrians and bicyclists but safety of all persons going through the intersection is always the primary objective. It is recognized that maintaining an efficient operation usually results in a safer operation. The City strives to maintain as efficient an operation as possible without any compromise in safety.

Delay and Stops

The objective is to reduce overall delay and stops as much as possible in order to reduce congestion and subsequent emissions. There does have to be some balancing to ensure that delays do not become intolerable on minor approaches or for pedestrians. The following guideline is provided:

1. Utilize shortest possible cycle lengths. The typical maximum cycle length is 100 seconds with some groups of intersections running at 110 seconds during peak periods only.

2. Utilize, when possible, possible, half cycle or 2/3 cycles to reduce side street delay at intermediate signals which have limited demand.

3. Utilize free and flash operation during significant off peak periods as long as progressions between closely spaced intersections on major arterials are not affected.

4. For major street segments in the downtown grid, a maximum of one stop per cycle for vehicles traveling through is an appropriate goal. It is best for arterial access roads to provide for no stops in the peak direction.

Progressive Flow

Providing consistent progressive flow on the main streets and arterials is the primary goal but this is best accomplished while maintaining reasonable speeds and not creating long side street or pedestrian crossing delays. The following are general guidelines:

1. It is appropriate to use lead/lag phasing where necessary to maintain proper progressive flow. If turning phases are not protected-only, caution may be used to avoid creating traps. Where protected/permissive phasing is utilized, the proper signing to warn of opposing traffic having extended greens may be installed.

2. Minimum, pedestrian and max 2 recalls may be used as necessary to maintain progressive flow where a non-call could lead to an excessive delay or an increased number of stops along the main road travel route. Recalls may also be necessary for lagging left turn phases to maintain progression for the through movement.

3. As much as possible, if there are no other conflicting criteria, progression may be provided on minor and circulating streets.

4. Plan transitions may be scheduled to avoid peak travel times, shift changes at hospitals, school arrival and departure times, and 10 minutes prior to train arrivals at or near train stations. Transitions may occur on the hour, 20 minutes after, or 40 minutes after for both time-of-day and responsive mode plan selection.

Queue Management

It is paramount to time critical intersections in a manner that does not create spillback and gridlock events. If necessary, police may be utilized at peak times and seasons to help prevent gridlock at key locations. Of particular concern are the following:

1. Bank Street (Martine Av. to Hamilton Av.)

2. Bloomingdale Road (Maple Av. to Westchester Av.)

3. Hamilton Avenue (MLK Blvd. to Bank St.)

4. Main Street (Battle Av. to So. Lexington Av.)

5. Main Street (Mamaroneck Av. to No. Broadway)

6. Mamaroneck Avenue (Main St. to Martine Av.)

7. Mamaroneck Avenue (Livingston Av. to Maple Av.)

8. Maple Avenue (Bloomingdale Rd. to Mamaroneck Av.)

9. Tarrytown Road (I287 to Battle Av.)

10. Westchester Avenue (Paulding St. to White Plains Av.)

Splits may be adjusted by creating different versions of the same plan (i.e., Plan 11 instead of Plan 1) to mitigate near "hot spot" locations at critical time periods. Such split altered or alternate plans are utilized near arenas, hospitals, schools, and the railroad stations. Temporary free operation may also be considered for such applications.

Clearance and Gap Times

Clearance, gap, and extension times are values that may be designed to match the need of each set of traffic conditions. Some guidelines to follow include the following:

1. It is appropriate for pedestrian clearances to use 3.5 ft/s walking speed for calculation while including the time for the yellow interval. Where there is unusually high senior presence such as near senior housing or the Senior Center, a walking speed of 3.0 ft/s may be used if possible.

2. Vehicle yellow intervals may typically be 3.2 s and range from 3.0 to 4.5. The all-red interval may typically be 2s and range from 1 to 3.5 depending on the intersection dimensions and prevailing speeds.

Gap and extension times may typically be 3.0 s with a range of 2.0 to 5.0 allowed when either unusual traffic or failed detection equipment may require a change in settings.

APPENDIX C

TECHNIQUES FOR DETERMINING WHETHER TO COORDINATE SIGNALS AND ESTABLISHING NETWORK BOUNDARIES

If signals are sufficiently closely spaced, coordinated signals can minimize delay and stops by providing progressions or green waves for vehicle flows. Isolated (noncoordinated) operation may be preferred when:

- Signal spacing is too distant to permit flows to progress.
- The cycle length needed by a key intersection is considerably different from that best suited to the remainder of the network.
- The intersection is saturated and considerations such as control of queue length dominate the timing pattern.

Limitations on the ability of coordinated signals to service the platoon of vehicles arriving at a downstream intersection result from the length of the travel time of the platoon between these intersections. In addition, the propensity of the platoon to dissipate (alter its shape from the pattern developed after it is released by the green signal at the upstream intersection) owing to traffic turning into the arterial and the "friction" of the roadway also limits the benefits of coordination. This is schematically shown in Figure C1 along with Table C1 that establishes the friction level (Robertson and Hunt 1982).

Although simulation is probably the best way to establish the need for coordination and the coordination boundaries, a number of techniques have been described for providing guidelines for coordination including the following.

INTERCOORDINATION DESIRABILITY INDEX. [*SOURCE*: CHANG AND MESSER (1986).]

The Intercoordination Desirability Index is described here:

$$I = \left(\frac{0.5}{1+t}\right) * \left(\frac{q_{MAX}}{q_T} - (N-2)\right)$$

where:

t = link travel time in minutes;

q_{MAX} = straight through flow from upstream intersection (VPH);

q_T = sum of traffic flow at the downstream approach from the right turn, left turn, and through movements of the upstream signals, divided by the number of arrival links at the upstream intersection;

N = Number of arrival lanes feeding into the entering link of the downstream intersection.

I may range from 0 to 1.0. Interconnection is advised when I exceeds 0.35.

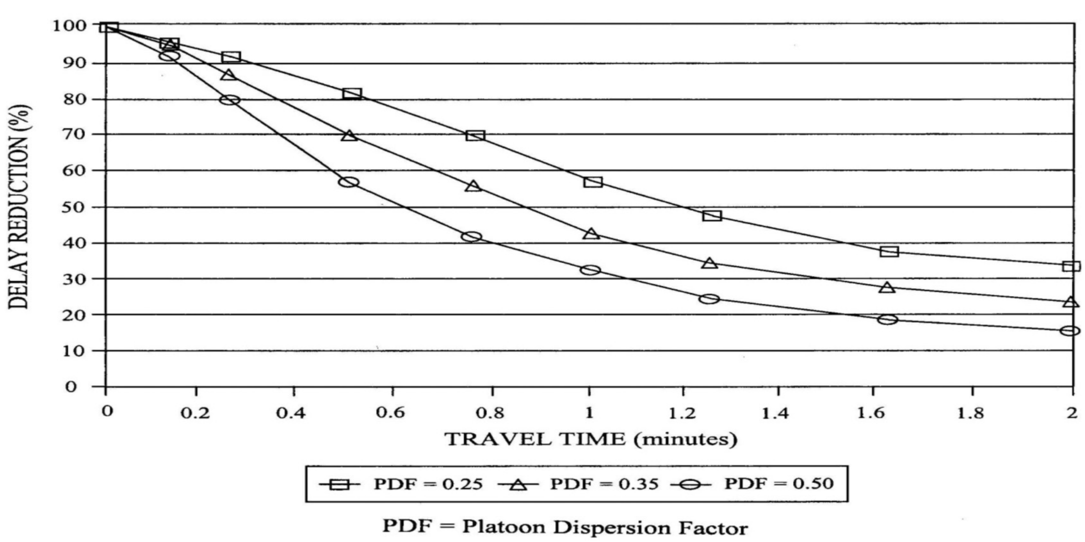

FIGURE C1 Reduction in delay through coordination. (*Source*: Robertson and Hunt 1982.)

TABLE C1
REPRESENTATIVE VALUES FOR PLATOON DISPERSION FACTOR

PDF Value	Roadway Characteristics	Conditions
0.5	Heavy friction	Combination of parking, moderate to heavy turns, moderate to heavy pedestrian traffic, narrow lane width. Traffic flow typical of urban CBD.
0.35	Moderate friction	Light turning traffic, light pedestrian traffic, 11 to 12 ft (3.4 to 3.7 m) lanes, possibly divided. Typical of well-designed CBD arterial.
0.25	Low friction	No parking, divided, turning provisions 12 ft (3.7 m) lane width. Suburban high type arterial.

Source: Fambro et al. 1991. CBD = central business district.

COUPLING INDEX. [*SOURCE*: HOOK AND ALBERS (1999).]

The theory is based upon Newton's law of gravitation, which states that the attraction between two bodies is proportional to the size of the two bodies and inversely proportional to the distance squared. The relationship is:

$$CI = V/D^2$$

where:

CI = Coupling Index (unitless),

V = Traffic volume for period analyzed (1,000 vehicles/hour),

D = Link distance (mi).

Coordination is always advised when the coupling index exceeds 50, coordination is desirable when CI is between 1 and 50, and coordination is not needed when CI is less than 1.0.

STRENGTH OF ATTRACTION INDEX. [*SOURCE*: HOOK AND ALBERS (1999).]

In the Strength of Attraction Index, the desirability of coordinating two adjacent intersections is based on the intersection spacing (link distance), link traffic volume, link travel speeds, and platoon interference (i.e., on-street parking maneuvers, driveways, etc.). The strength of attraction between intersections, for a given time period, is calculated from the following formula:

$$AF = I * V * (S/D)^2$$

where:

AF = strength of attraction (unitless),

I = platoon interference (unitless),

V = volume for the time period analyzed (vehicles/h),

S = speed (mi/h),

D = link distance (ft).

Platoon interference is a unitless value describing interference of the platoon as it progresses down the street. For simplicity, a platoon interference factor of 2.0 can be used for roadways without parking, 1.5 for roadways with parallel parking, and 1.0 for roadways with angled parking. The relative values between intersections may be considered in determining optimum signal groupings. There is no absolute strength of attraction at which coordination may or may not occur, however a natural breakpoint of approximately "1" appears to exist.

COUPLING INDEX. [*SOURCE*: BONNESON (2009).]

The Coupling Index, CI, is provide by:

$$CI = V/L$$

where:

V = 2-way volume (veh/h)

L = segment length (ft).

CI may be used to establish the potential for coordination according to the following:

- 0.3 or less — unlikely to benefit from coordination
- 0.3 to 0.5 — segment likely to benefit from coordination if mod-segment access point activity is low and turn bays are provided on the major street at each signalized intersection
- 0.5 or more — likely to benefit from coordination.

These techniques may be used to establish section boundaries. In many cases, particularly where arterials intersect, the traffic engineer's knowledge of corridor travel patterns and land use patterns influence intersection assignments to traffic sections.

NETWORK DECOMPOSITION AND SIGNAL TIMING OPTIMIZATION

Lieberman and Chang (2005) describe an approach for decomposing a grid network into its constituent arterial subsystems for the computation of optimal signal timing plans and the integration of these plans to form a network-wide signal timing plan. A signal timing plan generator (RT/IMPOST) is described.

REFERENCES

Bonneson, J., S. Sunkari, and M. Pratt. *Traffic Signal Operations Handbook*, Report FHWA/TX-09/0-5629-PI, Texas Transportation Institute, College Station, Mar. 2009.

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Hook, D. and A. Albers, Comparison of Alternative Methodologies to Determine Breakpoints in Signal Progression, In Conference Proceedings, 69th Annual Meeting of the Institute of Transportation Engineers, 1999.

Lieberman, E. and J. Chang, "Optimizing Traffic Signal Timing through Network Decomposition," *Transportation Research Record: Journal of the Transportation Research Board, No. 1925*, Transportation Research Board of the National Academies, Washington, D.C., 2005, pp. 167–175.

Robertson, D.L. and P.B. Hunt, "A Method of Estimating the Benefits of Coordinating Signals by TRANSYT and SCOOT," *Traffic Engineering and Control*, Vol. 23, No. 11, 1982, pp. 527–531.

APPENDIX D

NORTH CENTRAL TEXAS COUNCIL OF GOVERNMENTS RANKING MODEL

This appendix, largely abstracted from the reference, provides an example of a priority process for identifying candidate intersections for signal retiming.

The NCTCOG ranking model is based on the existing traffic conditions. The variables used in the model and their weights are discussed in this section.

VARIABLES

Total Delay

Delay is the most frequently used measure of effectiveness for signalized intersections. Delay can be quantified in many different ways: stopped time delay, approach delay, travel time delay, and time-in-queue delay (Roess et al. 1998). Travel time delay is used in this research. Travel time delay of an individual vehicle is the difference between the measured travel time and the travel time at the desired speed. Measured travel time is taken as an average of travel time in both directions of travel. The desired speed is taken as the posted speed. In this model, delay is used on an aggregate basis, and it is calculated here:

DPV = delay/vehicle/intersection

= (measured travel time – desired travel time)/(number of intersections) (1)

Total delay/ intersection = $DPV \times ADT$ (2)
Where ADT is the average daily traffic.

Number of Stops

The number of stops is taken as the average of the number of stops counted in both directions of travel along the corridor. To get the aggregate value, this average value per intersection is multiplied by the ADT.

Number of stops per intersection = (Number of stops/number of intersections) × ADT (3)

System Type

There are three types of existing systems. A value of one indicates that all intersections are part of an existing interconnected system with communications. A value of two indicates that some but not all intersections are part of an existing interconnected system with communications. A value of three indicates that there is no system (currently an isolated operation).

Weightings

The weighting for each factor is allocated by an expert group. The weightings are presented in Table D1.

TABLE D1
VARIABLES AND WEIGHTINGS

Variable	Weighting
Total Delay (DELAY)	50
No. of stops (STOPS)	30
System type (SYSTEMTYPE)	20

Calculation of Rank Order

Using the weightings applied by the NCTCOG, the following equation is developed.

Total Score(s) = (Delay/Max(Delay)) • 50 + (Stops/Max(Stops)) • 30 + System_Type • 20 (4)

Where System_Type = 1.0 for type 1 (all signals interconnected)

0.5 for type 2 (some signals interconnected)

0 for type 3 (all signals isolated).

Quantitative variables DELAY and STOPS are normalized by dividing the maximum value from all of the candidate corridors, which precludes any single variable dominating the total score because of its magnitude relative to the other variables. After normalization, each variable is expressed on a zero-to-one scale, and the weights are an expression of the relative importance of each criterion. The maximum value of a variable in the given data is used for normalization.

REFERENCES

Pulipati, S.B., *Regional Prioritization of Corridors for Traffic Signal Retiming*, University of Texas, Arlington, 2006.

Roess, R.P., E.S. Prassas, and W.R. McShane, *Traffic Engineering*, 2nd ed., Prentice–Hall, Englewood Cliffs, N.J., 1998.

APPENDIX E

COST AND BENEFIT ANALYSIS

The following publication, Chien et al. 2006 [© 2009 Institute of Transportation Engineers, 1099 14th Street, NW, Suite 300 West, Washington, DC 20005 USA, www.ite.org (used by permission)], provides an example of a cost and benefit analysis. It describes the techniques employed as well as the results.

Cost and Benefit Analysis for Optimized Signal Timing—Case Study: New Jersey Route 23

THIS STUDY DEVELOPS A PRACTICAL METHOD TO CALCULATE COSTS AND BENEFITS OF THE IMPLEMENTATION OF OPTIMAL SIGNAL TIMING PLANS WITH SYNCHRO. A SEGMENT ON ROUTE 23 IN NEW JERSEY IS USED AS A CASE STUDY. RESULTS SHOWED A SUBSTANTIAL BENEFIT IN REDUCING SIGNAL DELAYS, FUEL CONSUMPTION AND VEHICULAR EMISSIONS.

BY STEVEN I. CHIEN, PH.D., KITAE KIM AND JANICE DANIEL, PH.D.

INTRODUCTION

With the increasing dependency on automobiles and trucks to transport people and goods, signalized traffic control systems become a critical element of a transportation network. Although traffic signals are placed to regulate the flow of vehicles, negative impacts include increased travel time, fuel consumption and vehicle emissions.

Optimization of signal timing has been recognized as a viable way to improve the efficiency of surface transportation systems. Synchronizing and optimizing signal timing along an arterial or in a network results in smoother traffic flows that increase roadway capacity and reduce delay.

A number of previous studies have been identified in which major benefit components are quantified, including reduced travel time, delay, vehicle stops, fuel consumption, or vehicle emissions.[1–3] This study develops a practical method that collectively quantifies the benefit of signal optimization on a heavily traveled corridor—Route 23 in northern New Jersey. Analysis of re-optimization of the signal time under different rates of traffic growth is conducted.

METHODOLOGY

The cost of a transportation investment in economic terms is the value of the resources consumed to achieve expected benefits. The cost and benefit (C/B) analysis discussed in this feature aims to define and formulate all cost and benefit components associated with the implementation of optimal signal timing.

In general, the cost considered in this study is classified into three major components: engineering services; hardware; and administrative.

The benefit consists of the reduced delay and fuel consumption and improved safety, throughput, customer satisfaction, or environmental impact, classified into three components: road users' time; fuel consumption; and vehicle emissions.

To conduct a C/B analysis, both the cost and the benefit should be quantified and then converted into a monetary value. The configuration of the solution approach for this study is shown in Figure 1.

Cost Model

Before conducting a C/B analysis, it is essential that the studied cost and benefit components are carefully classified. Cost estimation generally is straightforward and, in most signal optimization projects, consists of location-dependent engineering service, hardware installation and administrative costs. The cost associated with signal optimization for intersection i is formulated as:

$$C_{I_i} = C_{E_i} + C_{H_i} + C_{A_i} \quad (1)$$

where

C_{I_i} = total cost ($)
C_{E_i} = engineering services cost ($)
C_{H_i} = hardware cost ($)
C_{A_i} = administrative cost ($)

Accordingly, the total cost (C_T) for optimizing signal timing for all intersections is the sum of cost (C_{I_i}) at intersection i. Note that engineering services and administrative costs are based on the entire studied route.

Benefit Model

The components considered in the benefit model are formulated with required data (such as traffic volume, vehicle composition, speed, travel time,

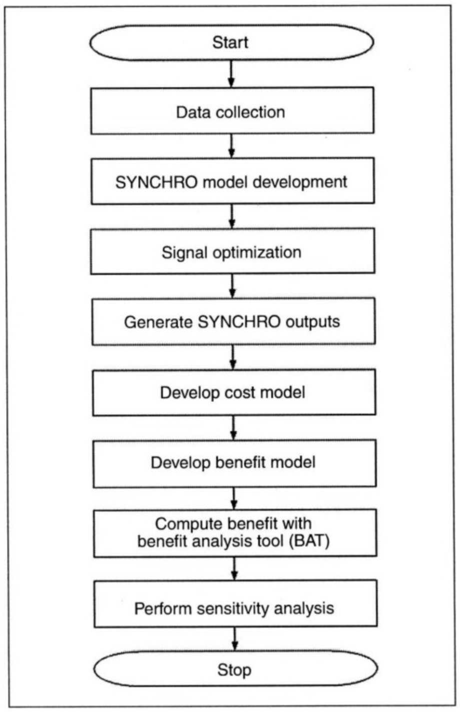

Figure 1. Configuration of study approach.

value of time and vehicle occupancy), which include savings of road users' time, fuel consumption and vehicle emissions.

Road users' time: The estimation of reduced users' travel time resulting from optimal signal timing is a primary component of the benefit model. The reduced user cost can be obtained from the saved travel time multiplied by the value of users' time. Travel time savings are based on the difference in delays before and after the implementation of signal timings optimized by SYNCHRO.

However, the delay estimated with SYNCHRO is vehicle-based. Therefore, by introducing vehicle occupancy, the user cost can be converted into traveler-based cost savings. According to the Highway Economic Requirements System, the vehicle occupancy weighting factor can be obtained using Equation 2: [4]

$$V_{WF} = \left(V_{OC} \times \frac{V_S}{100}\right)_{auto} + \left(V_{OC} \times \frac{V_S}{100}\right)_{truck} \qquad (2)$$

where
V_{WF} = vehicle occupancy weighting factor (persons per vehicle)
V_{OC} = average vehicle occupancy (persons per vehicle)
V_S = vehicle split ratio (percentage)

Therefore, the road users' cost saving is:

$$TS_{RU} = V_T \times V_{WF} \times D_S \qquad (3)$$

where
TS_{RU} = road users' cost saving (\$)
V_T = value of time (\$ per person-hour)
D_S = travel time saving (vehicle-hour)

Note that D_S can be directly obtained from SYNCHRO outputs.

Fuel consumption: An estimate of fuel consumption before and after the implementation of optimal signal timing is based on vehicle miles traveled, delays and number of vehicle stops. The formula used in SYNCHRO to approximate fuel consumption is:

$$FC = TT \times K_1 + TD \times K_2 + ST \times K_3 \qquad (4)$$

where
FC = fuel consumption (gallons)
TT = total travel (vehicle miles traveled)
TD = total delay (vehicle-hour)
ST = total stops (stops per vehicle-hour)
$K_1 = 0.075283 - 0.0015892 \times V + 0.000015066 \times V^2$
$K_2 = 0.7329$
$K_3 = 0.0000061411 \times V^2$
V = Cruise speed (miles per hour)

The saving of FC is based on the reduced fuel consumption multiplied by the unit price of gasoline. Thus:

$$F_S = \Delta FC \times P_f \qquad (5)$$

where
F_S = reduced fuel consumption cost (\$)
ΔFC = reduced fuel consumption (gallons)
P_f = unit price of gasoline (\$ per gallon)

Vehicle emission: The reduced vehicle emission cost is defined as the reduced fuel consumption multiplied by the emission production factor. Pollutants considered in this study include carbon monoxide (CO), oxides of nitrogen (NOx) and hydrocarbons (HC). HC are a group of chemical compounds composed of carbon and hydrogen. When in gaseous form, HC also are called volatile organic compounds (VOC). Equation 6 is formulated to approximate pollutants emission rates directly observed from SYNCHRO output:

$$E_m = \Delta FC \times P_m \qquad (6)$$

where
E_m = emission rate (grams) of pollutant m
m = index of CO, NOx and VOC
P_m = emission production factor (grams per gallon) of pollutant m

Table 1. Benefit model decision variables.

Decision variable	Value: Cars	Value: Trucks	Sources
Value of time (V_T)	\$12.75	\$21.25	New Jersey Department of Transportation. "Road User Cost Manual." 2001.
Vehicle occupancy (V_{OC})	1.59	1.0	Nationwide Personal Transportation Survey (1995).
Vehicle split (V_S)	98 percent	2 percent	Traffic Volume Data (NJDOT) (2002)
Gas unit price	1.7 (\$ per gallon)*		www.newjerseygasprices.com (2004)
Pollutant unit price			
CO	0.0063 (\$/kilogram)		Small, K. and C. Kazimi. "On the Cost of Air Pollution from Motor Vehicles." *Journal of Transport Economics and Policy,* Vol. 29, No.1 (1995): 7–32; as in Gillen, D., J. Li, J. Dahlgren and E. Chang. "Assessing the Benefits and Costs of ITS Projects: Volume 2: An Application to Electronic Toll Collection." California PATH Research Report, UCB-ITS-PRR-99-10, Institute of Transportation Studies, University of California, Berkeley, CA, USA, 1999.
NOx	1.28 (\$/kilogram)		
HC	1.28 (\$/kilogram)		

* Note: Benefit would be increased if current gas unit price (\$2.5 per gallon) applied.

Note that the values of 69.9, 13.6 and 16.2 are recommended emission production factors for estimating the emission rates of CO, NOx and VOC calculated by SYNCHRO, respectively. Thus, the benefit of emission cost can be computed from the reduced vehicle emissions multiplied by the pollutant unit price of CO, NOx and VOC (for example, \$0.0063 per kilogram, \$1.28 per kilogram and \$1.28 per kilogram, respectively), as shown in Table 1.[5,6]

Total Benefit

Note that the benefit estimation discussed in this study is an hourly basis from SYNCHRO output for a.m., noon and p.m. periods. The daily benefit defined here is the sum of three-hour benefits. Therefore, the total daily benefit denoted as B_{day} is:

$$B_{day} = B_{AM} + B_{NOON} + B_{PM} \tag{7}$$

where
B_{AM}, B_{NOON} and B_{PM} represent benefits in \$ per hour achieved in the a.m., noon and p.m. periods, respectively.

The annual benefit measured is calculated from the number of weekdays multiplied by the daily benefit computed in Equation 7. Note that the number of weekdays per year is assumed to be 261 = (365(days/year) − 52(weeks/year) × 2). Thus, the annual benefit (B_{year}) is:

$$B_{year} = B_{day} \times 26 \tag{8}$$

Note that the accuracy of benefit estimation may be improved further if B_{day} of the optimal timings is based on traffic volume in every hour of a day.

CASE STUDY

The New Jersey Department of Transportation (NJDOT) is redesigning signal timing plans for a 12-mile section of New Jersey Route 23 consisting of 19 signalized intersections from milepost 14.98 to 27.30. To conduct the C/B analysis of implementing optimal signal timing over the segment, required data (including intersection turning movement counts, roadway geometric features and existing traffic signal timings) were collected and used to develop SYNCHRO models. The developed models then were used to optimize traffic signal timing plans for a.m., noon and p.m. periods and to evaluate benefits for the studied route.

The calculation of benefits was performed by a developed benefit analysis tool (BAT), based on the difference between measures of effectiveness before and after implementing the signal timing plans optimized with SYNCHRO. As shown in Figure 2, BAT was designed to compute benefits automatically with selected SYNCHRO outputs and with specified parameters illustrated in Table 1. BAT demonstrated itself as efficient in calculating benefits resulting from various traffic growth rates, which were adopted for the sensitivity analysis discussed later in this feature.

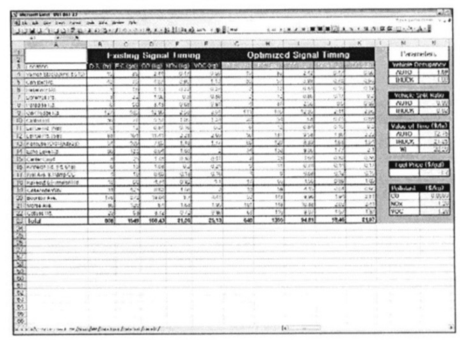

Figure 2. Benefit analysis tool (BAT).

Table 2. Total costs.

Cost component		Cost ($)
Engineering services	Data collection	0*
	Network modeling	
	Signal timing optimization	70,255
	Preparing new timing directives	
Administrative	Implementing signal timing	3,239
Hardware		0**
Total		73,494

* Note: Data provided by NJDOT.
** Note: No hardware expenses required.

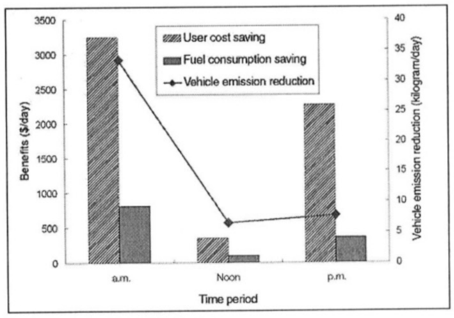

Figure 3. Benefits of optimal signal timing.

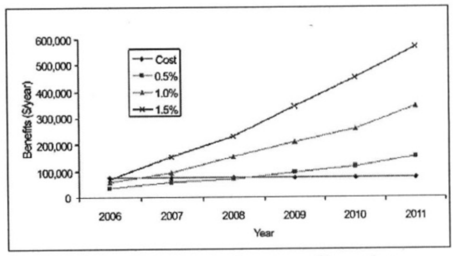

Figure 4. Benefits and costs versus time for various traffic growth rates.

Cost Estimation

Because the optimized signal timing plans considered in this study could be implemented without purchasing new hardware, the costs involved would consist of only engineering services and administrative costs. The engineering services cost would include collecting traffic volume data, processing data, developing SYNCHRO models, optimizing signal timing and preparing new timing directives. Administrative costs included agency technical oversight and field implementation. The total cost of $73,494 and the itemized engineering services and administrative costs are summarized in Table 2.

Benefit Estimation

According to the results generated by SYNCHRO, the hourly-based total intersection delay at the 19 studied signalized intersections dropped from 808 vehicle-hours, 106 vehicle-hours, and 447 vehicle-hours in the a.m., noon and p.m. periods to 648 vehicle-hours, 89 vehicle-hours and 335 vehicle-hours, respectively. The total reduced delay was 289 vehicle-hours, equivalent to $5,864, as shown in Figure 3.

The reduction in fuel consumption cost was based on SYNCHRO outputs and gasoline price. The fuel consumed at signalized intersections was 1,461 gallons, 474 gallons and 1,263 gallons in the a.m., noon and p.m. periods, respectively, which was reduced to 985 gallons, 418 gallons and 1,050 gallons after implementing optimized signal timing. A total 745 gallons of fuel, equivalent to $1,266, was saved (see Figure 3).

Adjusting timings at signalized intersections may result in vehicle emissions reductions. The cost of reduced pollutant amounts (see Figure 3) was computed from the emission rate multiplied by the pollutant unit price suggested in Table 1. Vehicle emissions cost savings were $18 per day.

Based on Equations 7 and 8, the total daily and annual benefits after implementing the optimized signal timing were $6,694 per day and $1,747,049 per year. Therefore, the ratio of annual benefit and cost achieved was 24 to 1. It was found that the major benefit was from reduced users' cost, which was 82.0 percent of the total benefit. The reduced fuel consumption and vehicle emission costs were 17.75 and 0.25 percent of the total benefit, respectively.

Sensitivity Analysis

The purpose of sensitivity analysis is to evaluate the optimal timing to re-optimize traffic signals for the studied route. For efficient traffic operation, completely retiming traffic signals often is necessary. Ideally, signal timing should be reviewed every year; however, retiming of traffic signals should be economically justified.

The sensitivity analysis was performed by assuming various growth rates of traffic while maintaining other variables unchanged. Traffic growth rates were assumed to increase every year from 2005 to 2011. Three traffic growth rates (for example, 0.5, 1.0 and 1.5 percent) were applied and measures of effectiveness (for example, signal delay, fuel consumption and vehicle emissions) were estimated.

In Figure 4, the slope of the curve indicates that the yearly benefit is sensitive to traffic growth rates. For example, although the benefits of re-optimized signal timing from 2006 to 2008 are less than the cost if a traffic growth rate of 0.5 percent is considered, the benefit after 2009 will exceed the cost. Therefore, retiming traffic signals is recommended in 2009.

For traffic growth rates of 1.0 and 1.5 percent, retiming of traffic signals in 2007 is recommended. Note that the gasoline unit price applied is $1.7 per day. The benefit of fuel consumption increases if the actual unit gasoline price of $2.5 per gallon for year 2005 is applied.[7]

CONCLUSIONS

This study develops a systematic way to quantify the cost and benefit of signal timing optimization. A cost/benefit model was developed, in which three cost components (engineering services, hardware and administrative costs) and three benefit components (reduced users' cost, fuel consumption cost and vehicle emissions costs) were considered. A case study was conducted. The results revealed that reduced users' cost is the major benefit from retiming signals on the studied route.

To estimate benefit in a robust way, BAT was developed for evaluating the benefits before and after the implementation of signal timings optimized with SYNCHRO. The initial results showed that the benefits of implementing the optimal signal timing were $6,694 per day and $1,747,049 per year, and the resulting yearly benefit and cost ratio was 24 to 1.

Evaluating the benefits of reduced accident cost should be conducted with the application of accident data that would be based on optimal signal timings. Future studies should focus on improving the accuracy of benefit estimation by considering the impact of optimal signal timing during 24 hours of a day.

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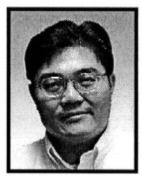

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Abbreviations used without definition in TRB Publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
SAFETY-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation

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