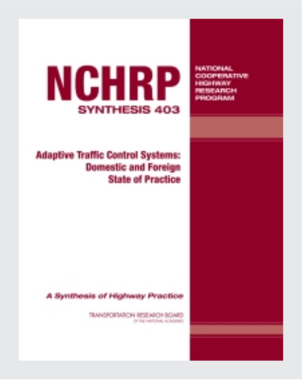


Adaptive Traffic Control Systems: Domestic and Foreign State of Practice

DETAILS

104 pages | | PAPERBACK
ISBN 978-0-309-14304-2 | DOI 10.17226/14364

AUTHORS

Aleksandar Stevanovic; Transportation Research Board

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP SYNTHESIS 403

Adaptive Traffic Control Systems: Domestic and Foreign State of Practice

A Synthesis of Highway Practice

CONSULTANT
ALEKSANDAR STEVANOVIC
Advanced Transportation Concepts, LLC
Salt Lake City, Utah

SUBSCRIBER CATEGORIES
Highways • Operations and Traffic Management

Research Sponsored by the American Association of State Highway and Transportation Officials
in Cooperation with the Federal Highway Administration

TRANSPORTATION RESEARCH BOARD
WASHINGTON, D.C.
2010
www.TRB.org

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.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Academies was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

NCHRP SYNTHESIS 403

Project 20-5 (Topic 40-03)
ISSN 0547-5570
ISBN 978-0-309-14304-2
Library of Congress Control No. 2009942376

COPYRIGHT INFORMATION

Authors herein are responsible for the authenticity of their materials and for obtaining written permissions from publishers or persons who own the copyright to any previously published or copyrighted material used herein.

Cooperative Research Programs (CRP) grants permission to reproduce material in this publication for classroom and not-for-profit purposes. Permission is given with the understanding that none of the material will be used to imply TRB, AASHTO, FAA, FHWA, FMCSA, FTA, or Transit Development Corporation endorsement of a particular product, method, or practice. It is expected that those reproducing the material in this document for educational and not-for-profit uses will give appropriate acknowledgment of the source of any reprinted or reproduced material. For other uses of the material, request permission from CRP.

NOTICE

The project that is the subject of this report was a part of the National Cooperative Highway Research Program conducted by the Transportation Research Board with the approval of the Governing Board of the National Research Council. Such approval reflects the Governing Board's judgment that the program concerned is of national importance and appropriate with respect to both the purposes and resources of the National Research Council.

The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the American Association of State Highway and Transportation Officials, or the Federal Highway Administration, U.S. Department of Transportation.

Each report is reviewed and accepted for publication by the technical committee according to procedures established and monitored by the Transportation Research Board Executive Committee and the Governing Board of the National Research Council.

Published reports of the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from:

Transportation Research Board
Business Office
500 Fifth Street, NW
Washington, DC 20001

and can be ordered through the Internet at:
http://www.national-academies.org/trb/bookstore

Printed in the United States of America

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. On the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Charles M. Vest is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, on its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academys p urposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both the Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. Charles M. Vest are chair and vice chair, respectively, of the National Research Council.

The **Transportation Research Board** is one of six major divisions of the National Research Council. The mission of the Transportation Research Board is to provide leadership in transportation innovation and progress through research and information exchange, conducted within a setting that is objective, interdisciplinary, and multimodal. The Board's varied activities annually engage about 7,000 engineers, scientists, and other transportation researchers and practitioners from the public and private sectors and academia, all of whom contribute their expertise in the public interest. The program is supported by state transportation departments, federal agencies including the component administrations of the U.S. Department of Transportation, and other organizations and individuals interested in the development of transportation. **www.TRB.org**

www.national-academies.org

Copyright National Academy of Sciences. All rights reserved.

NCHRP COMMITTEE FOR PROJECT 20-5

CHAIR

MEMBERS

FHWA LIAISON

TRB LIAISON

COOPERATIVE RESEARCH PROGRAMS STAFF

NCHRP SYNTHESIS STAFF

TOPIC PANEL

ACKNOWLEDGMENTS

Special thanks go to Peter T. Martin (Professor of Civil Engineering at the University of Utah) who introduced the author to the realm of Adaptive Traffic Control Systems and assisted in this project with many invaluable advices. The author would also like to thank Larry Head (Head of Systems and Industrial Engineering, University of Arizona), Nathan Gartner (Professor, Civil and Environmental Engineering, University of Massachusetts, Lowell), Bernard Friedrich, (Professor, Institute of Transportation and Urban Engineering, Technical University of Braunshweig, Germany), Yasuhiko Kumagai (Professor, Kochi University of Technology, Japan), Herman van der Vliet (Manager of Traffic Engineering, Peek Traffic B.V., Utrecht, Netherlands), Juergen Mueck (MOTION Project Manager, Siemens AG Industry Sector, Munich, Germany), and Frazer Johnson (Manager at Traffic Systems Branch, Road and Transit Authority, New South Wales, Australia) for their invaluable support in the initial stage of this study. Their initial comments regarding the scope and feasibility of this study helped to determine the course of the study. Very valuable assistance in the preparation of this synthesis was provided by the following group of ATCS vendors, developers, and users who helped to describe various ATCSs presented in this study: Bill Shao (Los Angeles Department of Transportation), Carlo Di Taranto (MIZAR Automazione, Italy), David Lucas (Arizona State University), Eddie Curtis (Federal Highway Administration), Farhad Pooran (Telvent), Filippo Logi (Siemens AG, Germany), Florian Weichenmeier (GEVAS Software, Munich, Germany), Frazer Johnson (Road and Transit Authority, New South Wales, Australia), Juergen Mueck (Siemens AG, Germany), Michael Sullivant (Rhythm Engineering), Pitu Mirchandani (Arizona State University), Robert Braun (Technical University of Munich, Germany), Steven Shaw (Road and Transit Authority, New South Wales, Australia), Steve Shelby (Siemens, USA), Tobias Pohlmann (Technical University of Braunshweig, Germany), Vito Mauro (MIZAR Automazione, Italy). The author is very grateful to the members of the study's topic panel who provided excellent feedback during the entire course of this study, which significantly improved organization and content of the study. The author also appreciated the assistance of Jon Williams (Program Director of Synthesis Studies) and other NCHRP synthesis staff who handled administrative matters of this project. Most importantly, special thanks go to Gail Staba, Senior Program Officer, who managed this project on behalf of NAS and TRB.

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 20-5, "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

Adaptive Traffic Control Systems (ATCSs), also known as real-time traffic control systems, adjust, in real time, signal timings based on the current traffic conditions, demand, and system capacity. Although there are at least 25 ATCS deployments in the United States, these systems may not be well understood by many traffic signal practitioners in the country. Their operational benefits are demonstrated, but there are still some reservations among the people in the traffic signal community. These systems are considered expensive and complex and they require high maintenance of detectors and communications.

The study methodology included three sequential efforts. The first focused on the selection of ATCSs, which are typically deployed in the United States (and worldwide) and identification of ATCS agencies. The next effort undertaken was a literature review that gathered and reported information about ATCS operations and deployments from previous studies. Finally, two electronic surveys were conducted: a shorter e-mail survey for ATCS vendors and a longer website-based survey for ATCS users. Responses were obtained from 34 of 42 agencies in North America, an 81% response rate. Also, 11 responses from agencies in other countries were obtained. Municipal and county traffic operations agencies were the major contributors among the 45 agencies that responded to the survey.

Aleksandar Stevanovic, Advanced Transportation Concepts, LLC, Salt Lake City, Utah, 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

1 SUMMARY

5 CHAPTER ONE INTRODUCTION
  Background, 5
  Study Goals and Objectives, 6
  Study Methodology, 7
  Agency Participation, 7
  Analysis Approach, 8
  Report Organization, 9

10 CHAPTER TWO OVERVIEW OF DEPLOYMENTS
  Introduction, 10
  Operational Environment, 10
  Implementation of Adaptive Traffic Control Systems, 10
  Summary, 16

17 CHAPTER THREE WORKING PRINCIPLES OF MAJOR ADAPTIVE TRAFFIC CONTROL SYSTEMS
  Introduction, 17
  Summary of Adaptive Traffic Control Systems Characteristics, 17
  Summary, 20

23 CHAPTER FOUR INSTITUTIONAL ASPECTS
  Introduction, 23
  Training, 23
  Operations, 24
  Maintenance, 26
  Summary, 27

28 CHAPTER FIVE SYSTEM REQUIREMENTS
  Introduction, 28
  Detection, 28
  Hardware, 30
  Software, 30
  Adaptive Traffic Control Systems and Microsimulation Tools, 32
  Communications, 32
  Summary, 35

36 CHAPTER SIX IMPLEMENTATION COSTS AND BENEFITS
  Introduction, 36
  Costs of Deploying Adaptive Traffic Control Systems, 36
  Evaluation Studies, 37
  Benefits from Adaptive Traffic Control Systems Deployments, 38
  Public Perception, 41
  Summary, 42

43 CHAPTER SEVEN LESSONS LEARNED
Introduction, 43
User Perspectives, 43
Summary, 45

47 CHAPTER EIGHT CONCLUSIONS

49 REFERENCES

50 ACRONYMS

51 APPENDIX A VENDORS' DESCRIPTIONS OF MAJOR ADAPTIVE TRAFFIC CONTROL SYSTEMS

83 APPENDIX B SURVEY QUESTIONNAIRE

96 APPENDIX C BIBLIOGRAPHY OF ADAPTIVE TRAFFIC CONTROL SYSTEMS

ADAPTIVE TRAFFIC CONTROL SYSTEMS: DOMESTIC AND FOREIGN STATE OF PRACTICE

SUMMARY

Adaptive Traffic Control Systems (ATCSs) adjust, in real time, signal timings based on the current traffic conditions, demand, and system capacity. The systems require extensive surveillance, historically in the form of pavement loop detectors, and infrastructure that allows for communication with the central and/or local controllers. Although there are at least 25 ATCS deployments in the United States, these systems may not be well understood by many traffic signal practitioners in the country. Their operational benefits have been demonstrated, but there are still some reservations among individuals in the traffic signal community. These systems are considered expensive and complex and they require high maintenance of detectors and communications. Although a few short surveys have been done, there has been no comprehensive survey that has addressed major problems with ATCS implementations.

The study methodology included three sequential efforts. The first focused on the selection of ATCSs, which are typically deployed in the United States (and worldwide), and identification of ATCS agencies that could be interviewed. The next effort was to conduct a literature review and gather as much information as possible about ATCS operations and deployments from previous studies. Finally, two electronic surveys were conducted: a shorter e-mail survey for ATCS vendors and a longer web-based survey for ATCS users. Responses were obtained from 34 of 42 agencies in North America, an 81% response rate. Also, responses were obtained from 11 agencies in other countries. Municipal and county traffic operations agencies were the primary contributors among the 45 agencies that responded to the survey.

Survey responses indicated that handling daily and weekly fluctuations in traffic flows is the major reason for ATCS deployments. When procuring an ATCS, agencies frequently consider multiple systems. On average, an ATCS installation takes approximately 18 months, from when funding is first available to the time the ATCS becomes fully operational. Most of the ATCSs that have been deployed during the last 20 years remain in operation. Agencies frequently expand their ATCSs and, in general, most of them are satisfied with their ATCS operations.

Review of the most widely used ATCSs has shown that various systems use similar strategies to cope with fluctuations in traffic demand and distribution. However, each tool is unique and without side-by-side comparison it is difficult to compare the algorithms and adaptive logic of the various tools. Field implementations of various tools are even more unique than their logics, which makes side-by-side field evaluations very expensive and therefore impractical. For this reason, among others, there are few studies available in the literature that document that the operational concepts of one particular ATCS are better than another.

ATCSs are considered more operationally demanding than conventional traffic signal systems, yet agencies are not able to support these systems in the same way they support the conventional systems. Unlike conventional systems that are maintenance-intensive, ATCSs require much more emphasis on the expertise necessary to execute their sophisticated operations. This switch in the type of labor (from maintenance to operations), which is needed to support proper ATCS operations, is often not recognized in the early stages of ATCS

procurements. An agency's inability to recognize a shift in the necessary labor requirements may cause some disappointment at the agency, and in the long term it may discourage an agency from expanding existing systems or from procuring a new ATCS.

There is a need for expertise for successful ATCS implementation. Although many agencies implement ATCSs to reduce labor-intensive maintenance of signal timing plans, survey respondents indicated that ATCSs are only tools for traffic management, and they need to be supervised and controlled by skilled engineering staff. Proper training and acquisition and retention of expertise within an agency are reported as the most important factors for alleviating institutional barriers for ATCS deployments. ATCS operations are often not perceived as being difficult; however, it appears that ATCS users are rarely given the opportunity to learn how to fully operate their systems.

A majority of the ATCS users rely on in-house expertise, which is more an indication of the inadequate resources available to hire outside support than that ATCS users are trained to fully control and operate their systems. Most ATCS agencies do not have financial resources to acquire comprehensive training for ATCS and most are short-staffed.

Detection requirements for ATCS are somewhat higher than those for conventional traffic-actuated control systems. Most ATCS users are satisfied with the way their systems handle minor detector malfunctions. ATCS users still struggle sometimes with handling ATCS-specific hardware; however, this is primarily an issue that can be resolved with better training of the technical staff.

ATCSs mainly operate on Windows-based platforms and are sometimes integrated with one of the available Advanced Traffic Management Systems. Integration with an Advanced Traffic Management Systems, which was formerly rarely done, has become more frequent with recent ATCS implementations. ATCS software is one of the system components that need improvement, as perceived by most users.

Interestingly, ATCS users did not find that ATCS communications cause many more problems than communications of conventional traffic control systems. However, communications play a much more important role in ATCS deployments (owing to the need for the frequent exchange of data between field controllers and other elements of the system). For this reason problems with communications are much more pronounced in ATCS operations. The cost of acquiring, maintaining, and repairing ATCS communications represents one of the major operational costs for ATCS users.

The survey results showed that ATCS installation costs per intersection are about US$ 65,000, which is higher than reported previously. Interestingly, results showed that ATCSs require less money than conventional traffic signals for physical maintenance. This finding contradicts the common belief within the traffic signal community that ATCSs are known for costly maintenance of their detectors and communications.

When ATCSs are evaluated most agencies prefer to hire outside consultants, who mainly perform field evaluations by means of a set of before-and-after studies. A majority of the user evaluations reported that ATCSs outperformed conventional traffic signal systems. When one considers that most of the agencies used (although not exclusively) coordinated-actuated control before ATCSs were deployed, there is no doubt that, in general, ATCSs outperform coordinated-actuated traffic control systems.

The benefits of ATCS deployments are not easily observable in oversaturated traffic conditions. Although ATCS users have found that their systems may delay the start of oversaturation and reduce its duration, ATCSs are not recognized as a cure-all for oversaturated traffic conditions. However, modifications of ATCSs to reduce oversaturation is often beyond the ability of

ATCS operational users; therefore, there is little evidence that can be used to draw conclusions about ATCSs' performances in instances of oversaturation.

Most users do not perceive that the performance of their ATCSs degrade over time. Public education campaigns about ATCS deployments are not particularly common or effective, as indicated by most of the ATCS users. Also, not many of the ATCS agencies conduct public perception surveys. Those agencies that do reported that results from such surveys are supportive approximately 50% of the time.

ATCS agencies were generally presently surprised by the system's ability to provide what was observed as "efficient operations" and to adjust to within-day and day-to-day traffic fluctuations. Negative surprises were mostly related to difficulties in learning how to operate the system and hardware issues (mostly communications). Lessons learned, from hindsight perspectives, can be summarized in four categories as needs for:

- Better local support from the vendors,
- Better planning for in-house operational and institutional support,
- A good preparation of the infrastructure (detection and communications), and
- Detailed pre-installation evaluation to estimate the operational benefits of the ATCS.

The following represents a non-inclusive list of actions that agencies that plan to deploy ATCSs might consider before making final decisions. However, it can be noted that every single ATCS deployment is idiosyncratic and every agency operates under slightly different conditions.

- Secure good local support from the vendor:
  - Ask your vendor for dedicated support field staff; insist on local vendor support.
  - Spend more time with the vendor's engineers and make sure they have the required expertise.
  - Keep a more watchful eye on the contractor installing the system.
  - Consider waiting for a fully vendor-supported system rather than a test application.
- Improve a planning process to avoid operational and institutional issues in-house:
  - Define a region that you want to start with; literature shows that starting with a larger region is better.
  - Allocate more time for debugging and expected technical difficulties.
  - Involve your operational staff in the decision-making process; do not rely only on the steering committee and project management.
  - Involve your staff in the operations and maintenance of the system—as early as you can and as much as your resources allow—as a result, you will be fully independent and acquire expertise earlier.
  - Expect that you will need more engineers and fewer technicians—your labor requirements will shift from maintenance-intensive to operations-intensive.
  - Have sufficient enough staff to be trained to manage your ATCS network.
- Prepare infrastructure (e.g., detection and communications) for an ATCS deployment:
  - Plan utilization of your existing equipment—some agencies are better off when retrofitting, others benefit more from installing new equipment.
  - Investigate detection technologies that will provide an acceptable level of reliability and accuracy for your ATCS operations.
  - Ensure that your local control firmware (if new) operates properly under ATCS and that your technicians are comfortable using it.
  - Review and plan reliable and affordable communications.
  - Consider installing other Intelligent Transportation System components to help you monitor your ATCS operations (e.g., closed circuit television cameras).
  - Ensure that ATCS algorithms and adaptive logics will fit your needs; if monitoring queues and oversaturation is your major problem, do not install an ATCS that cannot monitor those parameters and whose logic cannot help you to alleviate your problems.

  - If more detection is required, plan your actions and perform a cost–benefit analysis to investigate how much detection is needed and what system can be optimal with new detectors.
- Conduct a detailed pre-installation evaluation to estimate operational benefits of the ATCS before deciding to implement the system:
  - Gather more before-and-after data; make sure that you really need an ATCS—sometimes a good coordinated-actuated control can be as good as an ATCS.
  - If your intersections have regularly repetitive traffic conditions an ATCS may not be necessary.
  - Run the operations with traffic signals under actuated coordination (if possible) before deploying an ATCS.
  - If extensive capital costs for intersection infrastructure are needed (e.g., geometric re-configuration, replacement of signals, and detection) seriously consider an ATCS—it will remain in better shape than conventional traffic control regimes in the years to come.

Overall, most of the surveyed ATCS users (73%) would install the same system again. Users with more signals under an ATCS have better experiences with ATCS operations. Major reasons that prevent ATCSs from further expansions or new ATCS deployments are high costs related to operating and maintaining an ATCS (e.g., employing and training the staff). More signals under an ATCS attract more attention within the agency, more resources to operate and maintain ATCSs, more staff to develop and maintain in-house expertise, and finally more attention from ATCS vendors. Smaller systems tend to have more problems in securing funding and hence their overall experience with ATCSs is not as positive.

CHAPTER ONE

INTRODUCTION

The findings presented in the study were based on a literature review [conducted to gather as much information as possible about Adaptive Traffic Control Systems (ATCS) operations and deployments from previous studies] and two electronic surveys: a shorter e-mail survey for vendors or developers of 10 major ATCSs and a website-based questionnaire for agencies that deploy ATCSs. The survey was originally distributed to 42 agencies that run ATCSs in North America (United States and Canada) and several dozen locations around the world. Numerous follow-up requests were made, by e-mail and telephone, to remind agencies that had not yet responded asking them to participate. Responses were obtained from 34 of the 42 agencies in North America using an ATCS, an 81% response rate. Also, 11 responses were received from agencies in other countries. Of the North American agencies, 42% were municipal entities, 20% were counties, 13% were state agencies, and 25% were other types of entities. This chapter will define and introduce ATCSs. A short history of ATCSs and their classifications will be provided. Major ATCSs in use throughout the world will be identified along with the agencies that operate these systems.

BACKGROUND

An ATCS adjusts, in real time, signal timing plans based on the current traffic conditions, demand, and system capacity. An ATCS is defined broadly, in the previous sentence, so as to include all major ATCSs that may vary significantly in their levels of responsiveness, algorithmic framework, and detection. However, ATCSs, as defined in this report, exclude any traffic-responsive pattern selection and purely actuated (free or coordinated) types of traffic control. An ATCS usually includes algorithms that adjust a signal's split, offset, phase length, and phase sequences to minimize delays and reduce the number of stops. The system requires extensive surveillance, historically in the form of pavement loop detectors, and a communications infrastructure that allows for communication with the central and/or local controllers.

Emergence of ATCSs during the 1970s and early 1980s was largely attributable to a failure of traffic-responsive pattern-selection systems to efficiently respond to changes in traffic demand. In the early 1970s, there were a few attempts to develop ATCSs; however, there was no success with these early trials (Holroyd and Hillier 1971). At that time, traffic signal practitioners believed that fluctuations in traffic flows could be addressed through the development of several timing plans covering various traffic-demand scenarios and a good selection process triggering replacement of these timing plans. However, several experiments around the globe, of which the most prominent was done by the FHWA in Washington, D.C., showed that traffic-responsive pattern-matching systems have serious operational problems (Fehon 2005). The experiments showed that traffic control based on traffic-responsive pattern selection is not efficient. By the time one pattern transitions to another, traffic demand may change and the newly introduced pattern may no longer reflect current traffic conditions. Furthermore, transitions themselves may represent a disruption to traffic. The increasing frequency of pattern changes may improve matching between signal timings and traffic conditions, but the system may spend most of the time in transitioning, which may cause a continuous disruption to traffic.

To solve this problem, traffic engineers in Australia and the United Kingdom responded by investigating adaptive control of signal timings, which resulted in the development of the two most widely used ATCSs: the Sydney Coordinated Adaptive Traffic System (SCATS) (Lowrie 1982) and the Split Cycle Offset Optimization Technique (SCOOT) (Hunt et al. 1981). Development of these systems was quickly followed by a series of other new ATCSs. However, some of these new ATCSs abandoned conventional signal timing structures constrained by cycle lengths and offsets and, instead, offered new approaches that were mostly based on various techniques of mathematical programming: OPAC (Optimization Policies for Adaptive Control) (Gartner 1982) and PRODYN (Programming Dynamic) (Henry 1983). At that time, OPAC, PRODYN, and SPOT (System for Priority and Optimisation of Traffic) (Donati et al. 1984) were largely concerned with the operations of single intersections. Soon thereafter, UTOPIA (Urban Traffic Optimisation by Integrated Automation) was combined with SPOT to account to changes at the network level (Mauro and DiTaranto 1990).

Although most of these developments were taking place in Europe, at approximately the same time the FHWA initialized development and deployment of ATCSs in the United States. The Adaptive Control Software (ACS) program included a research project called Real-Time Traffic-Adaptive Signal Control Systems (RT-TRACS) that had gone through several stages to the point where there were several adaptive systems on trial in U.S. cities (Fehon 2005). Although the program initially sponsored development of five prototype strategies, only two of those were successfully tested and implemented in the field: a modified version of OPAC and RHODES (Real-Time Hierarchical Optimized Distributed and Effective System) (Head et al. 1992; Mirchandani and Head 2001). It is interesting to note that one of the first fully operating North American ATCSs, the Los Angeles Department of Transportation (LA DOT) ATCS, was not part of the RT-TRACS project, but was developed independently in 2003 by the city of Los Angeles.

Although early tests showed significant benefits of deploying OPAC and RHODES over fixed-time and actuated-traffic control, these two systems were not widely accepted in the United States. It appears that the major reasons for the limited deployments of these systems (as well as of all other major ATCSs) are the complexity of their logics, extensive detection requirements, necessary hardware upgrades, and the need to acquire new knowledge; in short—increased costs of operations and maintenance. To respond to these issues the FHWA launched the development of another ATCS whose major role was to be more simplistic, user-friendly, compatible with existing infrastructure (detection and hardware), and, overall less expensive to operate and maintain. The system is called ACS Lite and, although it has been tested in the field at four locations throughout the United States, is undergoing further enhancement (Shelby et al. 2008).

During this same period, SCOOT and SCATS were going through their own challenges with installations in the United States. Although their deployments in Europe, Australia, and Asia have steadily increased over the years they have struggled to increase their deployments in the United States. It appears that the major problems of early SCOOT and SCATS deployments in the United States were related to hardware and software, which were not fully customized for the U.S. market. Early problems with National Electrical Manufacturers Association (NEMA)-incompatible traffic controller hardware caused problems with some SCATS deployments in spite of the evident operational benefits. Some SCOOT deployments faced similar problems: suboptimal (for SCOOT operations) detection placements and somewhat user-unfriendly Open Virtual Memory System (VMS) interface negatively impacted SCOOT operations at some deployment sites.

Across the ocean, continental Europe struggled for a long time to keep up with the development of ATCSs in the United Kingdom, Australia, and America. French systems, such as CRONOS (Boillot et al. 1992) and PRODYN, which were early ATCS leaders in continental Europe, were not widely deployed in France or elsewhere. UTOPIA/SPOT appeared to work well in the networks of Italian cities for many public transit operations, but the first SPOT deployment abroad, in an environment with mostly vehicular operations, was not successful (Pesti et al. 1999). Development and application of German ATCSs, where SITRAFFIC MOTION (Kruse 1998) and BALANCE (Friedrich et al. 1995) represent the most notable systems, suffered for years before conditions were met for their more extensive deployments. German systems were facing a series of local institutional barriers and were seen by the professional community, for a long time, only as scientific research tools (Mueck 2005). It was not until the late 1990s that their benefits were recognized by traffic signal practitioners. Two major characteristics make German ATCSs distinctive: they attempt to address optimization of traffic signals based on network-wide changes in traffic demand by taking into consideration the estimated origin–destination flows in the network, and their logics are adjusted to work with German industry standards for local traffic controllers and public transit priority.

To summarize, ATCSs have been used since the early 1980s. Although there are at least 25 ATCSs deployed in the United States, these systems may not be well understood by many traffic signal practitioners in the country. Their operational benefits have been demonstrated in several cases, but some professionals argue that the systems are no better than good time-of-day (TOD) actuated-coordinated plans. Other issues with ATCSs include detector maintenance and communications problems and overall that these systems are considered expensive and complicated (Crenshaw 2000; Hicks and Carter 2000). Previous surveys on ATCS implementations provided some of the underlying sources of agencies' reluctance to widely deploy these systems. One of the major purposes of this study is to provide insight into all these issues from the perspective of an ATCS user to explain why ATCSs have not been utilized more, especially in the United States.

STUDY GOALS AND OBJECTIVES

The goal of this study was to summarize the state of practice in deploying ATCSs in North America, with an overview of ATCS deployments around the world. In this study, a broader definition of an ATCS was adopted to include all systems that adjust their signal timings in real time based on changes in current traffic conditions (excludes actuated and traffic-responsive pattern-selection systems). This study adopts an ATCS definition that includes all systems defined as traffic-responsive and traffic-adaptive control under the third generation of traffic signal control systems (Gordon and Tighe 2005).

The goal was achieved through the following objectives:

- Describing operational characteristics of major ATCS deployments;
- Identifying and describing widely deployed ATCSs, including a description of their working principles and operational requirements;
- Identifying operational advantages and disadvantages of deploying ATCSs, along with the problems with implementation and lessons learned;
- Identifying institutional problems at agencies that deploy ATCSs, along with documenting their experiences; and
- Investigating implementation costs and benefits perceived by ATCS users.

STUDY METHODOLOGY

The study methodology consisted of three tasks. The first focused on the selection of ATCSs, which are typically deployed in the United States (and worldwide) and identification of ATCS agencies that need to be interviewed. The second task was to conduct a literature review and gather as much information as possible about ATCS operations and deployments from previous studies. Finally, two electronic surveys were conducted: a shorter e-mail survey for ATCS vendors and a longer website-based survey for ATCS users.

Selection of Adaptive Traffic Control Systems and Adaptive Traffic Control Systems' Deployment Agencies

More than 20 different ATCSs have been developed during the last 30 years. However, only about a dozen of them have been applied in the real world and have more than one field implementation. In this study, it was decided to focus effort only on those systems that are implemented in the field. There were a few international systems that were not possible to describe in detail because their developers/vendors did not express interest in participating in the study. As a result, five U.S. and five international systems were investigated. Seven of those 10 systems are deployed in the United States, whereas the other three systems are currently deployed in Europe. The ATCSs considered in this study are ACS Lite, BALANCE, InSync, LA ATCS, MOTION, OPAC, RHODES, SCATS, SCOOT, and UTOPIA.

Selection of the agencies that deploy ATCSs was straightforward because the intention was to interview representatives from all public agencies in the United States that operate ATCSs. However, identification of these agencies was a somewhat difficult process because there is no single source containing such information. Therefore, identification of the ATCS agencies was based on the literature review and communications with traffic signal professionals, among which the study's panel members provided important assistance.

Literature Review

A comprehensive literature review on ATCSs included the use of print and online resources such as Transportation Research Information Services (TRIS), Transportation Research Records, and ASCE and Elsevier websites. Among the documents reviewed, some provided general descriptions of ATCS deployments and potential operational challenges. Others were about evaluations of specific ATCS implementations. In addition, few publications contained information about the classification of ATCSs and conventional traffic signal systems. There were many academic studies in which ATCS logics were evaluated in a microsimulation environment. Several documents from engineering conferences summarized the current status of ATCS deployments, with a future outlook of such systems. Analyzing these documents provided insight into ATCSs, created sound knowledge of existing implementation issues, and established a platform for evaluation of the survey data. The study itself does not refer to all of the documents gathered through the literature review. For the purposes of future research on ATCS, they are categorized and cited in Appendix C.

Surveys

The survey conducted under this study had two components. The first was a request sent by e-mail to all major ATCS developers or vendors to provide accurate and up-to-date descriptions of their systems. The ATCS vendors were requested to provide descriptions of the adaptive logic, hardware and software requirements, system architecture, detection requirements, and other special features of their systems. Most of the ATCS developers and vendors responded by identifying key studies that best describe their systems. Some ATCS vendors and users provided specific descriptions that they wanted to be part of this study. These descriptions followed the requested format but were sometimes broader than the scope of this study and therefore were edited.

The second component of the survey was a questionnaire that included quantitative and qualitative questions and was delivered through a web-based survey tool. A link for the questionnaire was sent to all ATCS users identified in the previous task and responses were collected over 3 to 4 months. The questionnaire was designed to gather as much information as possible on major North American ATCS deployments. It had several sections (e.g., system requirements, operations, training, and costs), each of which contained multiple questions. The questionnaire was designed to include both multiple-choice questions and open-ended questions. Multiple-choice questions were used when there was some certainty that the suggested answers adequately represented the range of likely answers. The option to add an answer was provided frequently. Open-ended questions were used when there was uncertainty as to the anticipated answer. The final version of the questionnaire (slightly different than the one offered on the web, owing to technical modifications that the web version requested) is provided in Appendix A.

AGENCY PARTICIPATION

The survey was originally distributed to 42 agencies that run ATCSs in North America (United States and Canada) and several dozen locations around the world. Numerous follow-up requests were made, by e-mail and telephone, to encourage those agencies that had not responded to participate in the survey. Table 1 is a list of those agencies that responded and the type of ATCS that these agencies operate. In a few cases, respondents who were interviewed do not currently work for agencies with an ATCS. However, they were recognized as the best experts to answer questions about the ATCSs even

TABLE 1
AGENCIES PARTICIPATING IN SURVEY

Agency	System
U.S. Deployments	
City of Longview, TX	ACS Lite
W.E. Stilson Consulting Group, LLC, Columbus, OH	ACS Lite
City of Little Rock, AR	InSync
California Department of Transportation — District 7, CA	LA ATCS
Culver City, CA	LA ATCS
Los Angeles Department of Transportation, CA	LA ATCS
City of Chesapeake, VA	OPAC
Town of Cary, NC	OPAC
Virginia Department of Transportation, VA	OPAC
Pinellas County, FL	OPAC, RHODES
City of Tucson, AZ	RHODES
Washington State DOT, WA	RHODES
City of Chula Vista, CA	SCATS
City of Gresham, OR	SCATS
City of Menlo Park, CA	SCATS
City of Santa Rosa, CA	SCATS
City of Sunnyvale, CA	SCATS
Cobb County, GA	SCATS
Delaware Department of Transportation, DE	SCATS
Florida DOT District 4, FL	SCATS
Minnesota Department of Transportation, MN	SCATS
Pasco County, FL	SCATS
Road Commission for Oakland County, MI	SCATS
Utah Department of Transportation, UT	SCATS
City of Anaheim, CA	SCOOT
City of Ann Arbor, MI	SCOOT
Collier County, FL	SCOOT
Orange County, FL	SCOOT
Reedy Creek Improvement District, FL	SCOOT
Short Elliott Hendrickson Inc., MN	SCOOT
International Deployments	
Econolite Canada Inc., Canada	RHODES
Dublin City Council, Ireland	SCATS
New Zealand Transport Agency, Auckland, NZ	SCATS
RTA, New South Wales, Sydney, Australia	SCATS
UOCT, Concepcion, Chile	SCATS
VicRoads, Victoria, Australia	SCATS
City of Blackpool Council, UK	SCOOT
City of Red Deer, Canada	SCOOT
City of Southampton, UK	SCOOT
City of Toronto, Canada	SCOOT
Derby City Council, UK	SCOOTS
Greater Manchester Urban Traffic Control Unit,	SCOOTS
Halifax Regional Municipality, Canada	SCOOTS
Hampshire County Council, UK	SCOOTS
I Mo TS Siemans Ltd., Beijing, China	SCOOTS

after they left their respective agencies. Also, in few instances, individuals from agencies that do not currently run ATCSs were interviewed. Some of these agencies went through an ATCS procurement process but decided not to install a system. Other agencies had only probationary deployments of their ATCSs, which were removed after the trial periods. Finally, some agencies that shut down their ATCSs were also interviewed. Overall, the response rate from North American ATCS users was slightly more than 80%.

ANALYSIS APPROACH

The analysis approach had two major components. First, whenever ATCS users responded to a multiple-choice question, results were reported in the text without (or with minimal) further manipulation. For the questions considered to be very important, the descriptions of the results were accompanied by corresponding charts or tables. In the event of open-ended questions, answers were categorized before being presented.

For very important open-ended questions, whose answers represented lessons learned on a certain subject, most of the responses were summarized in tabular format. Along with the data extracted from surveys, existing literature was used as material in the report.

REPORT ORGANIZATION

This report consists of eight chapters. The first chapter defines an ATCS, provides a short history of the ATCS, and covers scope, objectives, and study methodology. Chapter two deals with the operational background of the interviewed agencies and environments in which their ATCSs work. Chapter three summarizes some of the working principles of major ATCSs deployed worldwide as well as their hardware and software requirements and operational benefits. Chapter four covers institutional aspects of ATCS implementations, with a major emphasis on the training, operations, and maintenance of ATCSs. Chapter five covers system requirements, which are necessary for proper operations of ATCSs. The chapter describes ATCS needs for traffic detection, hardware, software, and communications and how those needs are perceived by ATCS users. Chapter six covers costs and benefits from ATCS implementations. Chapter seven provides lessons learned from various ATCS users' perspectives. Finally, chapter eight summarizes the information presented in previous chapters and offers conclusions that may help agencies interested in deployments. Separate lists of references and acronyms precede three appendices. Appendix A presents working principles of ten major ATCSs widely deployed in the United States and around the world. This appendix is based primarily on input from ATCS developers and vendors, and a comprehensive ATCS literature review. Appendix B contains the survey questionnaire. Appendix C provides an ATCS bibliography, categorized based on ATCSs described in the study.

CHAPTER TWO

OVERVIEW OF DEPLOYMENTS

INTRODUCTION

From the 45 agencies that responded to the survey (34 of 42 from North America and 11 agencies from other countries), the major contributors were municipal, county, and state traffic operations agencies with proportions of 42%, 20%, and 13%, respectively. All other organizations (regional organizations, federal government, consultants, and others) contributed with 25%. These findings indicated that the ATCSs are mostly operated by local agencies. Geographical locations of the ATCS deployments, which are found in Table 1, show that most of the U.S. ATCS users are located in California and Florida. This chapter identifies factors that dominate decisions to install an ATCS and those factors that describe the environment in which these systems operate.

OPERATIONAL ENVIRONMENT

Table 2 shows the number of signals operated by the interviewed ATCS agencies. It can be observed that some agencies operate a wide range of traffic signals. Several of the agencies have a very low percentage of signals under ATCS, whereas others run most of their signal operations through an ATCS. Statistics show that, on average, 25% of all signals under the jurisdiction of the interviewed agencies are operated under ATCSs. However, this number is heavily weighted by a few agencies that almost exclusively operate ATCSs. If one considers only systems where an ATCS is not the predominant type of traffic control (the number of signals under an ATCS is lower than the number of non-ATCS signals) the ATCS's share drops to 13%.

The survey results report that most of the interviewed agencies (80%) deployed ATCSs in the network with speed limits between 30 and 45 mph. Therefore, from that perspective, in most cases, ATCSs are installed in the environment in which they can contribute to reducing traffic congestion and improving overall operations.

Predominant speed limits on arterial streets may have an impact on the achievable benefits of ATCS implementation. If the speed limits are too low (e.g., lower than 30 mph), it may indicate that a lot of intermodal traffic exists and urban rights-of-way (ROWs) are shared between vehicles, pedestrians, bicyclists, etc. On the other hand, if the speed limit is too high (e.g., greater than 45 mph), it may be an indication that the network has a high-priority arterial(s) with intersections of streets with different priorities. In either circumstance, lower or higher speed limits, ATCSs may need additional fine-tuning to achieve acceptable operational results.

Another factor for the success of an ATCS is type of the network layout where an ATCS is deployed. Some ATCSs are known for their ability to provide balanced traffic control on grid networks. Others are known for their ability to adjust signal timings on corridor-type networks. In European cities, where road networks have more irregular shapes than in North America, controlling traffic on gyratory networks is also an important objective. Survey results show that approximately 42% of all agencies have deployed ATCSs solely on arterial networks, 10% deployed ATCSs on grid networks, and 33% deployed ATCSs on the combination of the two network types.

IMPLEMENTATION OF ADAPTIVE TRAFFIC CONTROL SYSTEMS

The type and quality of the pre-ATCS traffic signal systems is probably the most influential factor for determining the magnitude of benefits that can be achieved with an ATCS implementation. There is an abundance of studies that show benefits when an ATCS replaces an aged fixed-time, or actuated-isolated, traffic signal system. However, the benefits of replacing a properly fine-tuned actuated-coordinated control may not always be so evident. From that perspective, it is important to investigate what types of traffic control were run by responding agencies before they installed ATCSs. Statistics from the questionnaire reported that most of the agencies did not run a single type of control on their networks where ATCSs are now installed. Instead, most of them ran combinations of fixed-time and/or actuated controls where some intersections were coordinated, whereas the others were isolated. Table 3 shows the percentages of agencies that used relevant types of traffic control before they deployed an ATCS. These percentages show that actuated-coordinated control was the most widely used system in pre-ATCS networks.

There are many reasons why agencies that operate traffic signals may decide to deploy an ATCS. Some agencies are looking for a traffic control system that will be able to handle high day-to-day variations in traffic. For other agencies the primary reason for installing an ATCS may be the reduction in costs to retime signal timings every 3 to 5 years, which may be necessary owing to the steady increase in traffic demand and changes in traveler's patterns. Other major reasons for deployment of an ATCS are shown in Figure 1, which shows

TABLE 2
NUMBER OF SIGNALS OPERATED BY PARTICIPATING AGENCIES

Agency	Total No. of Signals	No. of Signals under ATCS
City of Menlo Park, CA	32	13
Reedy Creek Improvement District, FL	35	7
City of Blackpool Council, UK	77	50
City of Sunnyvale, CA	128	23
City of Gresham, OR	130	11
City of Longview, TX	132	16
City of Red Deer, Canada	133	89
City of Ann Arbor, MI	150	34
Town of Cary, NC	150	16
Collier County, FL	160	16
City of Chesapeake, VA	166	3
Unidad Operativa de Control de Tránsito, Concepcion, Chile	197	15
City of Santa Rosa, CA	200	9
City of Southampton, UK	200	200
Pasco County, FL	220	35
Hampshire County Council, UK	225	69
Halifax Regional Municipality, Canada	260	80
City of Chula Vista, CA	265	11
City of Anaheim, CA	300	0
City of Little Rock, AR	350	4
Pinellas County, FL	370	33
City of Tucson, AZ	375	15
Washington State DOT, WA	520	10
Cobb County, GA	526	74
Orange County, FL	572	70
Minnesota Department of Transportation, MN	675	0
Dublin City Council, Ireland	783	614
City of Minneapolis, MN	800	56
New Zealand Transport Agency, Auckland, NZ	800	750
Delaware Department of Transportation, DE	850	30
Utah Department of Transportation, UT	1,100	16
California Department of Transportation—District 7, CA	1,350	180
Road Commission for Oakland County, MI	1,500	650
City of Toronto, Canada	2,100	340
Greater Manchester Urban Traffic Control Unit, UK	2,200	2,200
Victoria Roads, Victoria, Australia	3,000	2,500
RTA, New South Wales, Sydney, Australia	3,800	3,500
Los Angeles Department of Transportation, CA	4,300	3,000

how ATCS users ranked nine different reasons for deploying such a system. Although there is no reason that is clearly predominant, one can observe that handling day-to-day and within-the-day traffic variations was ranked as the most important reason for deploying an ATCS. Surprisingly, if only a single factor with the highest rank for each ATCS deployment is considered then results show that such a system was most frequently deployed because:

- The agency served as a testing facility/early deployer of an innovative signal control method—seven ATCS deployments.
- It was recognized that an ATCS would help to resolve conflicts between vehicular traffic and other modes (pedestrian, transit, etc.)—five ATCS deployments.
- There was funding available for capital Intelligent Transportation System (ITS) projects and ATCS deploy-

TABLE 3
TRAFFIC CONTROL UTILIZED BEFORE ATCS DEPLOYMENT

Type of Traffic Control Before ATCS Deployment	Percent of Agencies Utilizing Traffic Control
Actuated coordinated	76
Fixed-time coordinated	31
Actuated isolated	22
Fixed -time isolated	7

Note: Total percentage exceeds 100 because some agencies deploy multiple types of traffic control at various intersections under their jurisdiction.

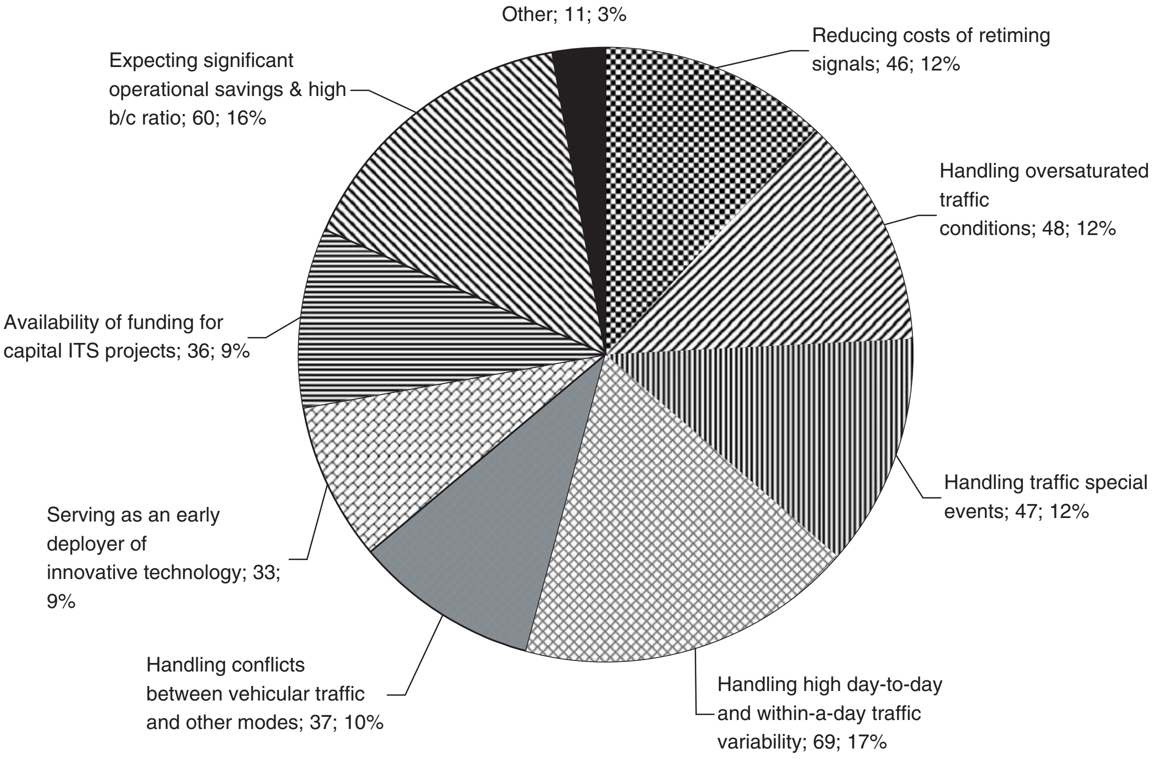


FIGURE 1 Major reasons for implementing an ATCS.

ment was funded under such a program—three ATCS deployments.

Some of these reasons (e.g., availability of funding or an interest in being an early deployer of a new technology) may indicate that sometimes decisions to deploy an ATCS are made at higher political levels at deploying agencies. If these ATCS deployments are made in an ad hoc manner or they are planned and executed without support from people who operate and maintain traffic control systems, the decision may have negative consequences. More research is needed to investigate how agencies make decisions to deploy ATCSs and whether decisions are made in coordination with operational staff.

Depending on an agency's preferences and defined procedures for procurement of ITS technologies the process of selecting an ATCS may be more or less complex. Some agencies conduct internal short reviews of the available systems before they make final decision of which system to install. Others go through a lengthy procurement process in which at times the lowest-bid option wins. Third, agencies hire outside consultants to do the review process and suggest the best ATCS for the operational conditions of an agency's deployment. The survey questionnaire asked agencies about their consideration of other ATCSs before the final selection was made. Most agencies responded that other systems were considered, although the current system was selected because it appeared that it was the best fit for the agency's needs. Of the 45 responding agencies, approximately 25% considered only the system that was later deployed. Approximately 12% of the agencies went through a complete ranking process, where multiple ATCSs were reviewed in the ATCS procurement process. Table 4 shows the major reasons that motivated agencies to select a particular ATCS for deployment. One particular agency (LA DOT) decided to further enhance its Urban Traffic Control System, which resulted in the development of its own ATCS platform.

TABLE 4
MAIN REASONS FOR SELECTING AN ATCS FOR DEPLOYMENT

Reasons to Select Current ATCS for Deployment	Percent of Agencies
Proven record of previous ATCS deployments	12
Only considered ATCS s known to work best for agencys network	12
Compatibility with existing communications and hardware	12
Friendliness of ATCS software	3

Note: Total percentage is lower than 100 because only 39% of the interviewed agencies responded to this question.

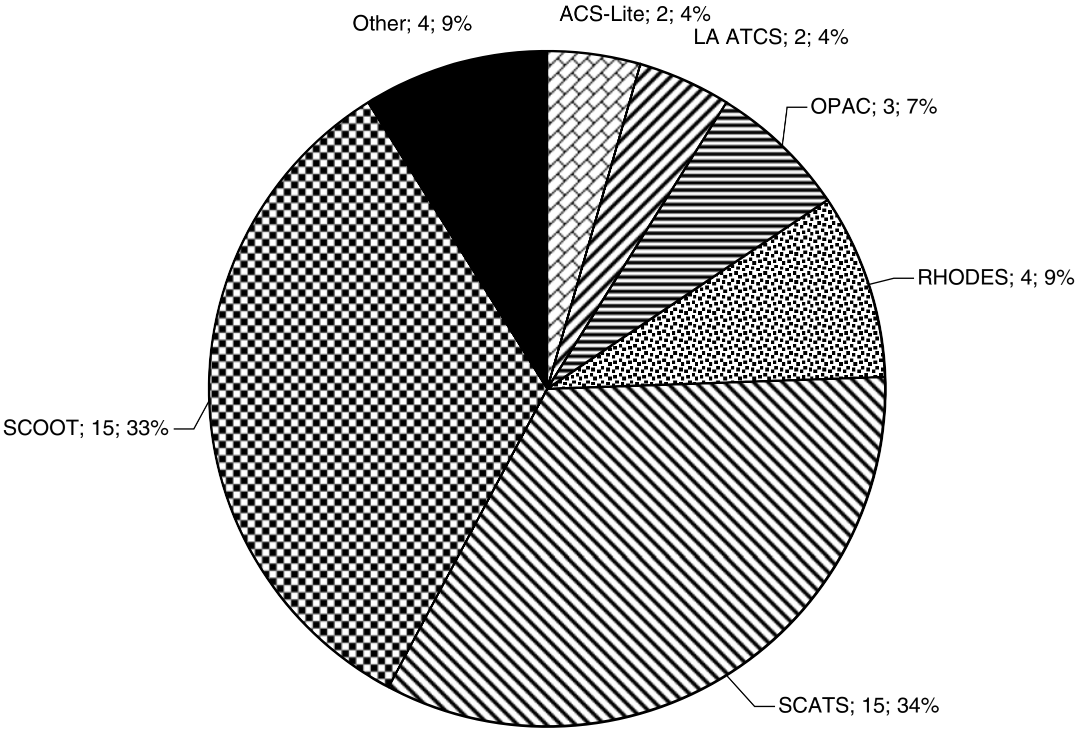


FIGURE 2 Market shares of various ATCSs.

Adaptive Traffic Control System Deployments

Figure 2 shows the percentages of the ATCSs deployed by the responding agencies; it is noticeable that SCOOT and SCATS are still the most dominant. However, these results are correlated to the maturity of the systems and their presence on the market. Although SCOOT and SCATS were developed almost 30 years ago, and they have been present in United States for approximately 15 years, several other systems are much younger. It can also be noted that some of the U.S.-developed systems have been deployed with support from the FHWA or similar U.S. federal agencies, whereas most of SCOOT and SCATS deployments were pure commercial projects. This dominance of SCOOT and SCATS is further confirmed among larger ATCS deployments; those having 50 or more intersections under an ATCS. Almost all larger ATCS deployments (except LA DOT) use either SCOOT or SCATS. The major reason for the popularity of SCOOT and SCATS may be found in the maturity of these systems and because they enjoy strong support from their developers and consultants. One of the limitations of the results presented in Figure 2 is that they do not include most of the ATCS deployments in continental Europe. Agencies from that part of the world did not show a great interest in participating in the survey.

The installation of an ATCS can be a lengthy and difficult process. If the network where an ATCS is being installed is in a high-growth area, interaction between ATCS installation and other ongoing projects may significantly affect installation time. The availability of local consulting, condition of existing infrastructure (detection, hardware, and communication), and availability of funding may all influence the duration of the installation process. ATCS agencies reported that, on average, installation of such a system takes approximately 18 months and is measured from the time when funding is made available until the ATCS is fully operational. Table 5 shows the distribution of ATCS deployment times for various installation intervals, which range from fewer than 3 months to more than 2 years.

TABLE 5
TIMEFRAMES FOR ATCS DEPLOYMENTS

Installation Intervals	Percent of Agencies
Less than 3 months	7
Between 3 and 6 months	7
Between 6 and 12 months	23
Between 1 and 2 years	33
More than 2 years	30

Of the 45 agencies that were interviewed, 38 have currently operational ATCSs. One agency only tested an ATCS and removed it after the probationary period owing to its incompatibility with the existing infrastructure (a communication problem between the ATCS and local controllers). Another agency considered the deployment of an ATCS, but found that benefits were too uncertain, and decided to operate an actuated-coordinated system. Finally, five agencies shut down their ATCS operations for various reasons. It appears that these shut-downs were not consequences of single problems but more a result of several factors that occurred simultaneously. The five agencies that shut down their ATCSs provided the following reasons to justify such actions:

- Agency 1—improper detection layout and other operational problems.
- Agency 2—multiple simultaneous events: budget reductions, staff reassignments, and construction projects resulting in significant removal of system detection.
- Agency 3—operational problems; agency did not shut down the entire system, but it converted most of the ATCS signals to actuated-coordinated operations.
- Agency 4—system incompatibility with ramp-metering where integration of arterial and ramp operations was required.
- Agency 5—no operational benefits achieved; problems with hardware and software.

Once an ATCS is installed, the system can provide not only traffic-adaptive operations but also other control modes (actuated-coordinated TOD plans, isolated control, etc.). The variety of traffic control systems offered under the ATCS umbrella provides agencies with the opportunity to run ATCSs 24 hours per day and 7 days per week. If agencies do not let the ATCS control traffic on a 24/7 basis this may indicate that they do not have full confidence in ATCS operations. Also, if an ATCS is working properly and an agency experiences its operational benefits it would be logical that the system be expanded (spatially) to other neighboring traffic signals or entire signal systems. The results from the survey indicate that the high costs of ATCS deployments are the most common obstacle to expanding current ATCSs temporally and spatially (in 50% of the cases). The second factor, by its importance, is the lack of traffic signal operations staff—a problem that can also be attributed to inadequate funding (12%). Finally, 13% of the agencies reported that the operational inefficiency of their ATCSs is the major reason why they have not expanded their systems. The following are examples of the agencies' responses:

- Insufficient staff and funding to operate and maintain;
- Poor communications between vendor and client;
- Not cost-effective if volume fluctuations are insignificant or where cycle lengths and splits are quite constrained to meet operational objectives;
- Because it is very expensive for the licensing fees and very sophisticated to set up and fine tune. In addition, it requires much vehicle detection that is well-maintained and working properly;
- Difficult to program and data intensive;
- High cost of supplying communications or low priority sites; and
- Only use it at times of high traffic flows as standard vehicle actuation is more reactive at quieter times when linking becomes less important.

Despite these difficulties, a significant number of the interviewed agencies have expanded their ATCSs since the initial deployments. Actually, only 30% of the agencies have *not* expanded their ATCSs at all. Fourteen percent of the agencies had one expansion of their systems, and another 14% had two expansions. Finally, 42% of the agencies expanded their ATCSs three or more times. Fifty percent of all these expansions were small expansions where a few neighboring intersections were added to the initial ATCSs, whereas the other 50% were major expansions onto neighboring corridors of traffic signal systems. Some agencies developed long-term expansion plans, where they steadily increase their ATCSs by a certain number of intersections per year.

Traffic Signal Operations Staff

The size and expertise of the traffic signal operations staff may significantly affect the success of an ATCS deployment, as well as deployment of any other traffic signal system. The size of the traffic signal operation team largely varies with the size of the agency and available financial resources. The survey results revealed that the traffic signal operations staff can be a single person or a team of more than 50 people (see Figure 3).

Figure 3*a* shows average, median, and mode values of the overall sample of interviewed agencies. Differences between statistics show that large agencies significantly increase the average number of staff employed, whereas median and mode more realistically show frequent, inadequate levels of staffing at small- and medium-size agencies. Figure 3*b* shows a relationship between the number of signals under an agency's jurisdiction and the number of signal timing staff. One could note that a linear relationship would not fit the data properly because it would set an intercept unacceptably high (~10), which would be a very unrealistic estimate. Overall, more than 25% of the agencies have five or fewer people in their traffic signal operations staff. These findings show that a significant portion of the agencies that operate an ATCS are understaffed and that a lack of qualified personal may be one of the major problems for potential performance issues of their ATCS deployments.

Most of the ATCS users reported that they are familiar with the operations of their systems. Thirty-one percent of the ATCS users know their systems very well, whereas 38% have a good working knowledge. Twenty-four percent of respondents understand their systems but do not consider themselves to

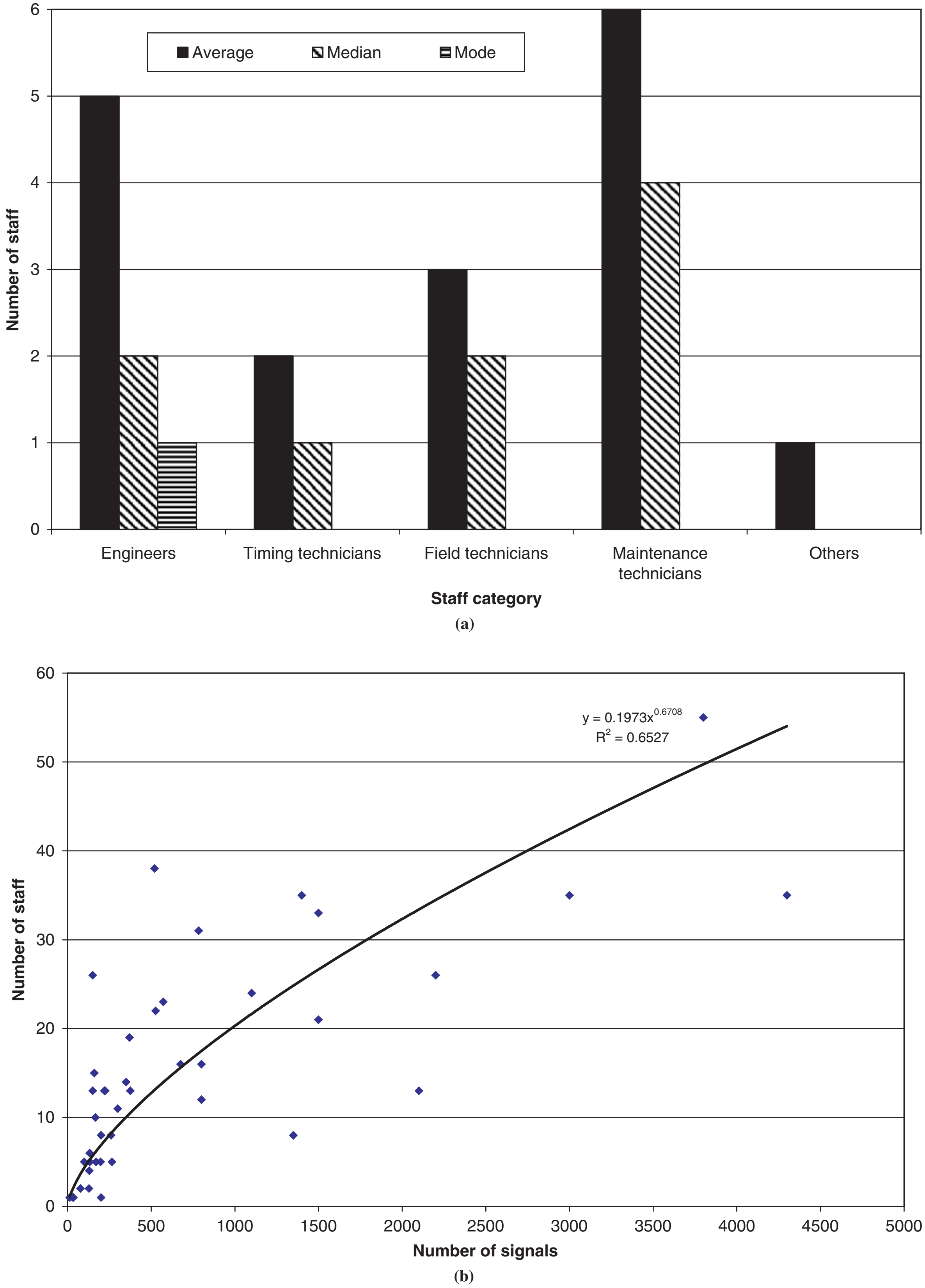


FIGURE 3 (*a*) Statistics of timings staff; (*b*) Number of signals versus number of staff.

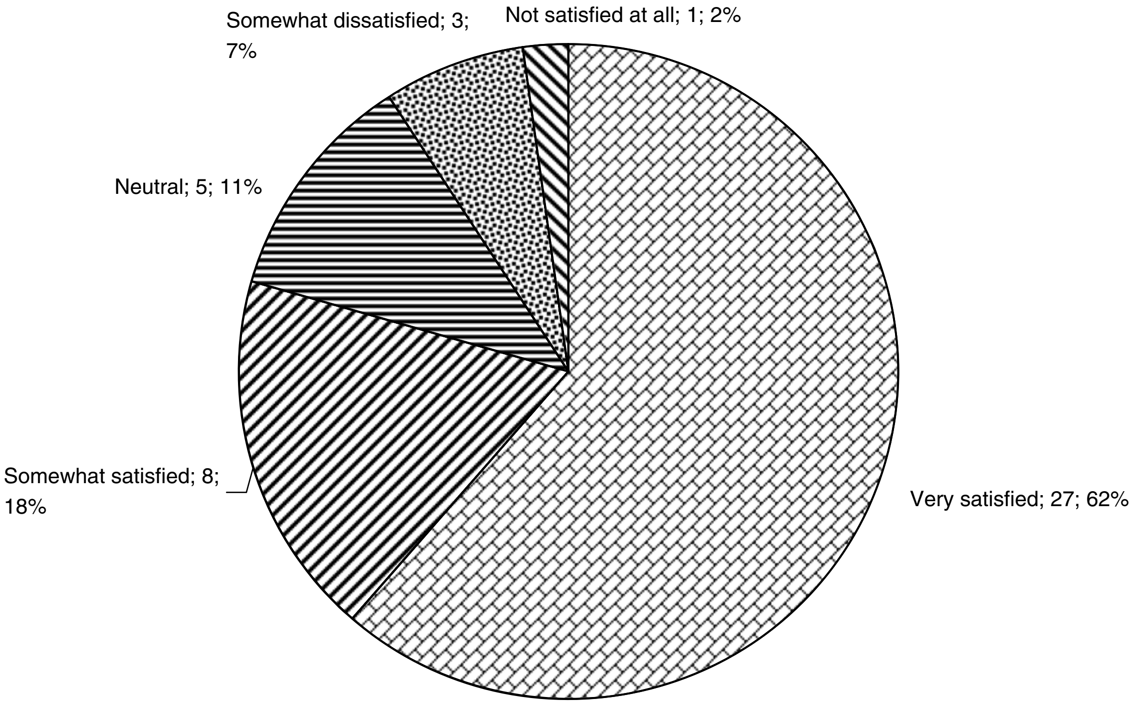


FIGURE 4 Satisfaction of ATCS users with their systems.

be specialists. Finally, 7% of the respondents have a limited understanding of their systems' operations.

In general, agencies are satisfied with their ATCSs. Eighteen percent of the respondents claimed that they are very satisfied, whereas 61% are only somewhat satisfied. Figure 4 also shows that approximately 11% of ATCS users do not see either advantages or disadvantages in using ATCSs, with approximately 10% not satisfied.

SUMMARY

This chapter presented the operational backgrounds of ATCS deployments and the institutional capacities of the agencies that deploy ATCSs. In general, agencies deploy ATCSs in operational environments where ATCSs are known to provide the best performance. For most of the agencies, traffic signals under an ATCS contribute from 10% to 30% of the overall signal population under their jurisdictions. Most of the agencies used (although not exclusively) coordinated-actuated control before ATCSs were deployed. Handling daily and weekly fluctuations in traffic flows is the primary reason for ATCS deployments. Most of the agencies, in one way or another, considered multiple ATCSs before they decided which ATCS to deploy. However, only a few of the agencies went through a comprehensive process of reviewing other ATCSs. On average, an ATCS installation takes approximately 18 months, from the time funding is available to the time an ATCS becomes fully operational. Most of the ATCSs (90% to 95%) that were deployed during the last 20 years are still operational. Although the agencies reported various factors that prevented them from expanding their ATCSs, most of the agencies (70%) have expanded their systems since the initial installation. In general, most of the agencies (79%) are satisfied with operations of their ATCSs. The next chapter describes the working principles of ten major ATCSs used throughout the world.

CHAPTER THREE

WORKING PRINCIPLES OF MAJOR ADAPTIVE TRAFFIC CONTROL SYSTEMS

INTRODUCTION

This chapter summarizes some of the working principles of major ATCSs deployed worldwide. Detailed descriptions of various ATCSs, based on information obtained from the systems' developer and/or vendors, are provided in Appendix A. Each of the ATCS descriptions primarily follows a format with the following subsections:

- Adaptive traffic control logic
- Hardware and software requirements
- System architecture and communications
- Detection requirements
- Special features.

Detailed descriptions of all ATCSs and their characteristics were beyond the scope of this study. This report could not address in detail all of the ATCSs that are currently used around the world. For some of the ATCSs, literature (in English) is scarce (e.g., PRODYN, CRONOS, and ITACA). Some other U.S. brands have a limited deployment history in the United States. Sometimes, the adaptiveness of these systems is claimed owing to the adaptive functionalities and features of their local controllers. This study covers only systems that can be recognized as full adaptive traffic control packages, with an identifiable adaptive framework (logic, detection, etc.), that have been deployed in the field. Some of the emerging or international technologies are still not properly described in the literature. Hence, Table 6 shows 10 ATCSs, with their developers and vendors that were found to be the most important, to be described in this study. Selection of the systems presented in Table 6 is based on several criteria, of which the most important are:

- Length of the presence on the market,
- Field deployments,
- Documented descriptions of the system (available literature), and
- Credibility of developer/vendor in ATCS field.

SUMMARY OF ADAPTIVE TRAFFIC CONTROL SYSTEMS CHARACTERISTICS

Operational Characteristics

ATCSs can be categorized in numerous ways. Some are known to operate best on arterial networks (ACS Lite and SCATS), whereas others are known for their adaptive operations in grid networks (e.g., SCOOT and UTOPIA). However, different concepts and operational features that drive these ATCSs do not always result in significantly different field performances. The following paragraphs review the conceptual differences of the systems described in this study.

Each of the ATCSs is somewhat unique. Therefore, comparison of the specific features of each of the ATCSs is almost impossible. Instead, this study identified and compared several principles that essentially describe various adaptive traffic control logics. Among the potential principles to be considered it was found that the following are of particular interest for the scope of this study:

- Detection,
- Type of action,
- Adjustment method,
- Time frame for adjustment,
- Hierarchical levels,
- Estimation through traffic modeling,
- Adjustments to signal timings,
- Flexibility to form regions,
- Support for vehicle-actuated operations, and
- Transit operations.

This list does not include at least a half dozen other principles that are nearly as important. For example, handling pedestrian operations and the ability to provide a framework for sustainable traffic signal operations have now become two of the most important principles in traffic signal operations. However, although some ATCSs are very advanced in this regard (e.g., SCOOT for pedestrian facilities), others simply rely on operations provided by local field controllers whose comparison is beyond the scope of this study.

Detection

Various ATCSs use different detection layouts to estimate the state of traffic, which is later used to develop strategies that adjust traffic control in a network. There are generally four major detector location types used by most ATCSs:

- Stop-line detectors (e.g., as seen in common actuated operations in the United States and SCATS).

TABLE 6
ATCS DESCRIBED IN THE STUDY

System	Developer/Distributor
ACS Lite	FHWA/Siemens ITS
BALANCE	University of Hanover, Germany/Gevas Software, Germany
InSync	Rhythm Engineering
LA ATCS	Los Angeles DOT/McTrans
MOTION	Technical University Munich, Germany/Siemens, Germany
OPAC	U. of Massachusetts, Lowell/PB Farradyne
RHODES	U. of Arizona, Tucson /Siemens ITS
SCATS	Road Transit Authority, Sydney, NSW, Australia/TransCore
SCOOT	Transport Research Laboratory, UK/Siemens UK
UTOPIA	MIZAR Automazione, Italy/McCain

- Near-stop-line detectors located close to the stop-line (10–60 m), which cannot be used (owing to their proximity to the stop-line) to easily calculate queue length by balancing inflows and outflows (e.g., as used in Germany by BALANCE and MOTION).
- Upstream (mid-block) detectors, which can be used to estimate reasonably long queue lengths (e.g., as seen at some Californian intersections).
- Upstream (far-side) detectors located at the exit point of the upstream intersection (as used by SCOOT, UTOPIA, ACS Lite, and optionally by RHODES).

Each of these detection layouts dictates, to a certain extent, the type of adaptive traffic control logic that is needed to use imperfect measurements of the current traffic state where imperfections are inherently caused by location, number of detectors, and accuracy of detection technology.

Type of Action

Some ATCSs proactively adjust traffic control to meet estimated traffic demand at each intersection before vehicles arrive. Other ATCSs react by providing feedback to the traffic measured during the previous interval. These two concepts are usually, but not necessarily, related to the location of detectors. If stop-line detectors are used alone, the ATCSs will usually provide feedback and respond with certain delay. Upstream detectors usually allow for a certain degree of proactivity, although systems that use these detectors rely more on traffic models and the estimation of traffic demand. In spite of the common belief that proactive systems work better than reactive systems, there is no hard evidence to support such a hypothesis. Some of the major systems combine two concepts for various segments of their operations. For example, SCOOT determines splits and offsets proactively, whereas the cycle length is computed reactively. ACS Lite is similar: splits are determined reactively, whereas the offsets are determined proactively.

Adjustment Method

There is a widely accepted notion among traffic signal practitioners that most ATCSs optimize signal timings. The reality is that some of them perform some kind of optimization, which is usually constrained by its domain or time allowed to conduct the optimization process. Some of these optimizations use heuristic techniques, whereas others use extensive search techniques, to find solutions. Others do not formally optimize (no search process and no objective function); instead, they adjust signal timings by using some heuristic methods and common traffic engineering concepts. Essentially we have three major types of adjustment methods:

- Domain-constrained optimization, where an optimization search domain is *very much* limited to avoid high fluctuations of signal timings to prevent negative transition effects (e.g., SCOOT—all parameters, ACS Lite—offsets).
- Time-constrained optimization, where the optimization search process is constrained by time and/or structural boundaries set by local controller policies (e.g., RHODES, OPAC, BALANCE, and MOTION).
- Rule-based adjustment, which covers any methods used to develop a (simple) functional relationship between parameters that describe change of traffic conditions and resulting signal timings.

Time Frame for Implementing New Signal Timings

Some ATCSs adjust some of their parameters every few seconds. Others adjust parameters every 10 to 15 min, similar to pattern-matching responsive traffic control systems. Some of the ATCSs combine the two approaches. Again, there is no evidence that the systems that respond faster are (always) better than the less responsive systems, although such a notion can be found in the literature.

Hierarchical Levels

It is interesting to note that all of the ATCSs considered in this report, in one way or another, operate on two or more hierarchical levels. Although some systems are seen as more hierarchical than others, they all have a component that uses operations of local controllers and also some tactical (or strategic) component that oversees the responsiveness of traffic control on a higher level, regardless of whether it is done in a centralized or in a distributive way. For example, SCOOT, which is often considered a major example of centralized (and tactical) ATCS, also uses demand-dependent features of local controllers to skip phases with no demand.

Estimation Through Traffic Modeling

The word "modeling" here refers to the use of macroscopic, mesoscopic, or microscopic models (by an ATCS) to estimate the current state of traffic, which is further used as an input to adjust signal timings. For example, analytical models that express relationships between measured and derived traffic variables (such as degree of saturation, phase utilization, etc.) do not conform to the definition of modeling as used in this section. SCOOT is famous for its model that estimates queue lengths based on flow-occupancy profiles from upstream detectors. SCATS does not use any traffic modeling in its operations. Most of the other ATCSs use models extensively. In general, models help ATCSs perform more proactively, although they also may introduce errors that can be propagated (spatially and temporally) during the course of ATCS actions. An extreme use of modeling is seen in the newly developed ATCS for New York City, where data from traffic detectors are used to populate a microsimulation model that is then run under a variety of traffic control strategies (within a 15-min time frame). In spite of its ultramodern approach of using a microsimulation model to investigate the quality of signal timings, the system requires that a specified traffic control strategy be confirmed manually (Xin et al. 2008).

Adjusted Signal Timings

Most ATCSs adjust three major types of signal timings: green splits, cycle lengths, and offsets. However, there are a few ATCSs that do not follow this rule either because they are still under development (e.g., ACS Lite) or because their operations are not based on all of these timings (e.g., RHODES, InSync, and some versions of OPAC do not use cycle lengths). Conversely, only a few ATCSs adjust or optimize phase sequencing in real time (e.g., BALANCE, MOTION, and InSync). This is primarily because frequent alterations in phase sequencing can cause negative impacts on traffic (frequent transitions).

Flexibility to Form Regions

For some of the ATCSs (e.g., SCOOT, SCATS, and LA ATCS) it is necessary to divide the entire area covered by the ATCS into those regions or subsystems of intersections that usually need to be coordinated. In such a case, a bordering intersection in one subsystem may sometimes benefit from leaving its current subsystem and joining the neighboring subsystem. If an ATCS supports automatic reconfiguration of the subsystems it is said that the ATCS supports flexible regions. SCATS is well known for its "marriage and divorce" logic, which supports automatic reconfiguration of the subsystems based on predefined criteria. Although SCOOT can do something similar, most of the other ATCSs either do not support such operations or information about such a feature is not easily available in the public literature.

Support for Actuated Operations

By actuated operations it is meant common gap-out operations executed by local controllers. Most of the ATCSs will set lower and upper boundaries for green splits. A lower boundary is usually defined as minimum green for each phase. Upper boundaries are usually defined by dynamic splits that are optimized by ATCS logic for each cycle (or even for shorter intervals). What happens in between defines whether an ATCS supports actuated operations or not. To further clarify this concept a distinction needs to be made between cases where an ATCS takes responsibility to end the green phase in the absence of traffic demand over a detector and where such a responsibility is transferred to a local intersection controller. For example, RHODES does not allow a local controller to make decisions based on local actuation. If RHODES is in its "Online" mode it will issue a force-off command to stop green for a phase. This command is based on RHODES traffic estimation and not on the common gap-out logic of a local controller. The RHODES concept does not transfer responsibility to gap-out operations to a local controller. On the other hand, SCATS, as well as some other ATCSs (e.g., BALANCE, MOTION, and ACS Lite), will allow the local controller to execute its gap-out logic in between the aforementioned lower and upper boundaries.

Transit Signal Priority

It is interesting to note that most of the ATCSs presented here provide some type of priority for transit vehicles. However, this priority is often provided at the local controller's level and is not offered as a result of comprehensive optimization where transit travel times (or delays) are integrated into the optimization structure that accounts for network-wide vehicular and transit performances.

Table 7 shows how each of the ten major ATCSs considered in this study are categorized for each of the ten principles. The information provided here is based on a comprehensive literature review and does not necessarily reflect how vendors

TABLE 7
OPERATIONAL CATEGORIZATION OF ATCS

ATCS	ACS Lite	BALANCE	InSync	LA ATCS	MOTION	OPAC	RHODES	SCATS	SCOOT	UTOPIA
Detection	SL, MB/ US	NSL	NSL	SL & US	NSL	MB & SL	MB & SL	SL, NSL, MB	US & SL	US & SL
Action	P & R	P & R	P & R	P & R	P & R	P	P	R	P & R	P
Adjustment	DCO	TCO	DCO	RA, TCO, DCO	TCO	TCO	TCO	RA	DCO	TCO
Time Frame	5–10 min	5 min	Phase/ Cycle/ 15 min	Cycle	5–15 min	Phase/ Cycle/ 5 min	Sec by sec	Cycle	Cycle/ 5 min	3 sec — Cycle
Level	C/L	C/L	C/L	C/L	C/L	C/L	C/L	C/L	C/L	C/L
Model	No	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
Timings	S, O	S, Cl, O, PS	S, Cl, O, PS	S, Cl, O	S, Cl, O, PS	S, Cl, O	S	S, Cl, O	S, Cl, O, PS	S, PS
Flexi Region	No	No	Yes	Yes	No	No	No	Yes	Yes	Yes
Vehicle Actuated	Yes	Yes	No	Yes	Yes	No	No	Yes	Yes	Yes
TSP	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Detection: SL = stop-line; NSL = near-stop-line; MB = mid-block; US = upstream.
Action: P = proactive; R = reactive.
Adjustment: RA = rule-based adjustment; DCO = domain-constrained optimization; TCO = time-constrained optimization.
Level: L = local; C = central.
Timings: S = splits; Cl = cycle length; O = offset; PS = phase sequencing.

and developers of ATCSs see their systems. One could also note that the categorization provided in Table 7 is based on information that is sometimes derived from limited systems' descriptions in the literature.

A detail discussion of the principles presented in Table 7 is beyond the scope of this study; however, a few interesting observations are:

- High similarities of the operations of MOTION and BALANCE reflect the concept that these two systems were developed in a similar environment of local German policies and standards.
- RHODES, OPAC, and InSync are systems that do not require local controllers to use their own actuated logic.
- SCATS is the only purely reactive system that does not use any traffic models (and yet it is one of the most widely used ATCSs).

Software, Hardware, and Communications

Table 8 provides examples of communications, software, and hardware requirements for the ten ATCSs described in this study.

SUMMARY

In summary, this chapter provided an overview of the operational characteristics of ten most-widely used ATCSs. Selected working principles were briefly described and ATCSs were categorized with emphases on their adaptive traffic control logics, systems' architectures, and detection requirements. The final sections of the chapter summarize, in tabular format, software, hardware, and communication requirements. The next chapter reports on institutional issues confronting most ATCS users, from installation through everyday operations and maintenance of ATCSs.

TABLE 8
SOFTWARE AND HARDWARE SPECIFICATIONS FOR ATCS

System	Controller	Software	Communications
ACS Lite	Siemens NEMA (M50 series) or 2070 (2002 TEES or later) with SEPAC NTCIP 4.01F firmware. Also run with Econolite ASC/2 with NTCIP firmware w/ACS lite support. Peek 3000E with external NTCIP translator. McCain 170E with BI-TRAN 233 firmware with ACS Lite support.	ACS Lite software running on field-hardened PC or central server (Windows XP).	Comm: Serial or Ethernet. Serial is single channel, where 9600 baud supports up to 8 signals. Faster serial can support more signals.
BALANCE	European controllers	GEVAS VTnet/View	ISDN dial-up line 2400 bps-modem wireless
InSync	Existing Controllers Cabinets require InSync processor to communicate with controller using detector cards	Internet access to InSync System through a local computer InSync System	Ethernet communication
LA ATCS	Model 170 Controllers/ 172.3 Firmware Type 2070 Controllers/ City of LA Software	PC ATCS/Traf Graph Editor	Dedicated central to field connection 1200 bps using time division multiplexing 4 intersections/communication channel No Peer-to-Peer communication needed Supports multiple communication media
MOTION	SITRAFFIC C8xx,C9xx Controllers Signalbau Huber Actros Controllers Older Siemens controllers	PC SITRAFFIC	V34 modem Ethernet Fiber-optic cable … Central control via wireless links using public communication channels such as Internet/GPRS
OPAC	Model 2070/multiple firmwares Model 170 with 68360 Processor/multiple firmwares NEMA Controllers VME Bus or equivalent	PC MIST	Dedicated central to field connection at 9600 baud or higher Peer-to-Peer possible through Central Supports all communications media
RHODES	2070 ATC with NextPhase-Adapt Controller Software Econolite ASC/2 with Adapt X interface software	RHODES Software on OS9/Windows/ Linux field-hardened, single-board computers	Peer-to-Peer over Ethernet; Bandwidth ≥96000 bps. Supports all communications media; preference is fiber optic.

(continued on next page)

TABLE 8 (*Continued*)

System	Controller	Software	Communications
SCATS	Model 170 controllers with SCATS conversion kit, which includes a new processor board with embedded software with 2070 or 2070 N controllers with SCATS proprietary controllers. NEMA AWA Delta 3N controllers. There are several RTA type approved SCATS controllers in current use sourced from Australia; i.e., Tyco Eclipse, QTC, Aldridge ATSC/4, Tyco PSC and a myriad of legacy controllers still supported; e.g., Phillips PTF.	PC SCATS	Requires 300 bps link to each controller using two-wire or equivalent. Multidrop system is supported that requires a two-wire line or equivalent to the first intersection in a cluster and then to each intersection in the cluster in a daisy chain ” configuration. SCATS supports various configurations that can utilize TCP/IP, leased line, and conventional telephony services (i.e., dial-up).
SCOOT	Eagle NEMA Eagle 2070/ SEPAC support for 170 can be provided	PBS with MS Windows Server 2003	Both SCOOT and ACTRA require a separate channel to controller from the central—at 9600 baud, 8 controllers can be supported.
		SCOOT algorithm and ACTRA	Supports all communications media; wireless typically not used.
UTOPIA	Peek’s EuroController with MDSL unit	PC-based software Logic is distributed over control units.	

CHAPTER FOUR

INSTITUTIONAL ASPECTS

INTRODUCTION

The deployment of an ATCS can be a powerful tool, and it requires an agency's commitment to staffing for operations and maintenance. ATCSs are often presented as a way to reduce labor required for repetitive development of signal timing plans. However, these systems cannot be considered hands-off types of systems. This chapter identifies institutional requirements for a successful deployment of an ATCS. In addition, the chapter reveals agencies' perceptions on operational problems with ATCSs. The final section of the chapter provides insight into the way agencies perceive maintenance of ATCSs.

TRAINING

It is critical that an ATCS agency acquire a level of knowledge that enables proper deployment, operations, and maintenance of the system. Without proper knowledge and technical expertise to operate an ATCS an agency can find itself in a hardware and software technology bind. If the agency does not have sufficient expertise, it needs to hire external consultants for any operational problems or the system will suffer. If there are no financial resources available to hire external consultants, or if the consultants are not readily available, the ATCS can go into a "hibernating mode"—it operates, but its performance will slowly degrade. In the long term, such hibernating systems may be left alone until they are replaced by conventional traffic signal control systems. Therefore, to acquire and retain the proper level of knowledge to operate ATCSs, agencies need to:

- Receive proper initial training at the time when the ATCS is initially deployed,
- Acquire continuous training and support to resolve operational issues, and
- Retain the expertise (personnel) during the life of ATCS operations.

ATCS users stated that, on average, their vendors spent approximately 25 person-days to provide the initial training to enable the users to operate their system. However, this number varies considerably among ATCS users. Some of the users received only a few days of training, whereas others were receiving vendor support for the first 3 to 4 months. In the second instance, it did not mean that the vendors needed that much time to train their users, but primarily that they were available during this time for consultation without additional cost (the costs of these services are usually included in the installation package). The estimated person-hours for the initial training might be taken with some reservation because some respondents could not provide an accurate estimate. Also, the level of initial training depends largely on users' budgets for ATCS deployments and the size of their systems.

In general, approximately 77% of ATCS users stated that they received adequate training. Of those who believe that the training was inadequate, 2% reported that the vendor/consultant was not interested in providing the training. Another 2% reported that the training was too expensive and the costs were the major reason that the agency did not pursue the full training. The remaining 19% of the interviewed agencies reported that the training was inadequate for other reasons, which are mostly associated with the lack of interest on user side to pursue the training.

Understanding the working principles of an ATCS is the major requirement to having an operationally successful ATCS. ATCS users do not find that the working principles of their ATCS are difficult. Some (18%) found that the working principles were difficult, but most of the ATCS users consider the principles to be easy. Figure 5 shows the detailed responses on the level of difficulty of ATCS working principles.

These results provide a somewhat unbalanced picture of how understandable ATCS working principles really are. Most ATCS vendors do not provide comprehensive training to enable their users to fully utilize their ATCSs. They usually explain generic principles of each system in a highly aggregated way during the initial days of ATCS deployment. In addition, users are usually given a level of training that supports only common every-day operations; customizing and operational reconfiguration of the system are beyond their level of expertise. In this way, ATCS users are inclined to hire vendors and/or consultants for any challenging problems (e.g., addition of a new intersection or reconfiguration of the existing system of an intersection). From that perspective, ATCS users are usually given an opportunity to perceive only the end user's side of the system. The real difficulties in operating many of the available system's bells and whistles are often not perceived by the users; hence, the bias reflected in the reported answers.

Once the ATCSs are in place and initial validation of the systems is complete, approximately 62% of ATCS users rely

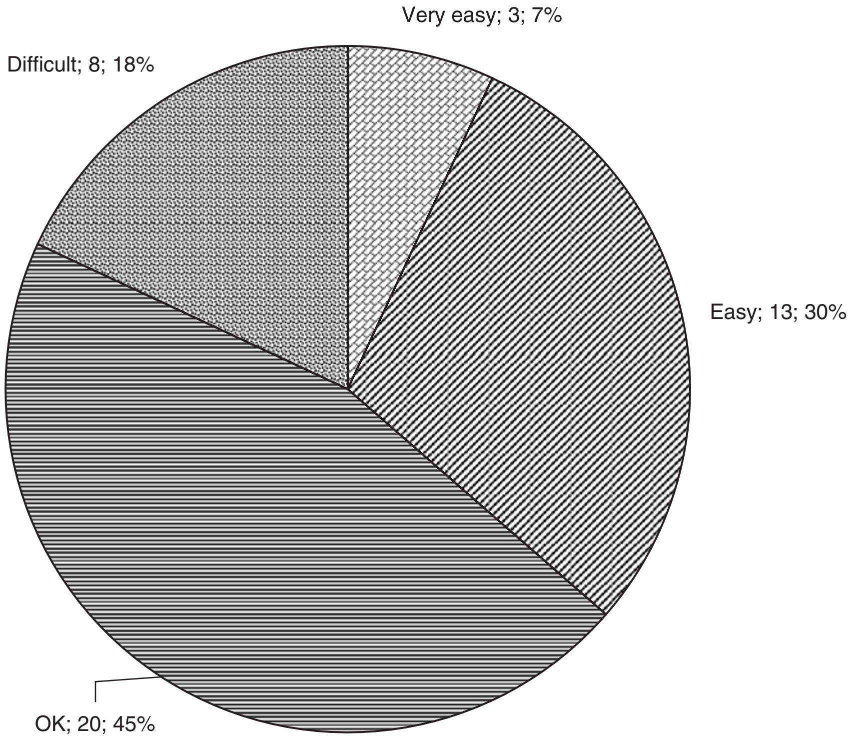


FIGURE 5 Difficulty in understanding working principles of an ATCS.

on their own (in-house) expertise. The others contract out to ATCS vendors either for all tasks (10%) or only for major modifications in the operations of their ATCS (29%). It is interesting to note that ATCS users with larger ATCS deployments (50 or more intersections under an ATCS) are more inclined to use their own expertise (70%). Level of expertise on an ATCS that stays within an agency tends to increase with the size of the ATCS installation and the financial resources available to keep that installation running.

When it comes to building in-house expertise, 57% of interviewed agencies would like to acquire such expertise to fully utilize the potential of their ATCSs. It does not appear that these agencies would have problems securing funding for such additional training programs. Only 2% of the agencies believe that such an educational effort would be too expensive. Seven percent of the ATCS users believe that there is no interest within their agencies for such a training program. More specifically, 12% of the all interviewed agencies recognize that such a lack of interest for full in-house expertise on the ATCS is associated with the concept that their ATCSs control only a small percentage of traffic signals under their jurisdiction. Therefore, the ATCSs do not attract enough attention from their agencies to warrant the full in-house expertise. Another 24% of the respondents are unable to provide resources for such training because of insufficient funding. In general, the problem is not so much finding the resources for the training itself as in having enough individuals to attend the training and take responsibility for the full in-house expertise on the ATCS.

OPERATIONS

The deployment of an ATCS can bring significant benefits to traffic performance on the network where it is installed and requires a commitment to staffing for operations and maintenance. ATCSs are often presented as a labor-saving alternative to conventional traffic control, as the signal timing plans do not need to be developed on a regular basis. However, an ATCS is not a hands-off type of system.

ATCSs are complex in operation, and it is believed that traffic engineers need at least four to six months to acquire a general understanding of these systems, whereas an experienced signal timing engineer needs about two months. These estimates indicate only the time needed to understand the system and not the time needed to become proficient. It may take years for a signal traffic engineer to acquire hands-on experience and become proficient with the system. For smaller agencies that run small-size ATCS deployments, retaining the ATCS-proficient staff becomes the most important ATCS-related issue.

Approximately 56% of the surveyed ATCS users find that these systems are more demanding for operations than conventional traffic control systems. Nine percent of that 56% find ATCSs to be much more demanding than other systems. Conversely, approximately 21% of ATCS users believe that ATCSs are less demanding. The remaining 23% perceive ATCSs as similar to their other systems. These answers are somewhat correlated with how the agencies operate and maintain the systems. An agency with enough resources to hire outside consultants for the smallest operational tasks of an ATCS may find it easier to operate their ATCS because it is mostly operated (everything but every-day operations) by a consultant.

Sixty percent of the interviewed agencies reported that they do not have enough staff to operate and maintain their ATCSs to the fullest potential. Many agencies reported that it is much easier to find funding for capital investments, such as an ATCS deployment, than for regular operations and maintenance of the existing technologies. A particular notion about ATCSs exists that implies that once they become operational they do not need much maintenance. This might be one of the major reasons that some of the ATCS deployments are understaffed. The reality is quite opposite; ATCSs need more high-expertise maintenance than regular traffic control systems. If such a need is not recognized by the agency there is a considerable chance that the ATCS will underperform and eventually even be replaced by a conventional traffic signal system. The respondents' answers on their annual budgets for ATCS operations agree with the previous responses about the shortage of staff. About 63% of the interviewed agencies do not have an annual budget (for operations and maintenance of traffic signals) that is large enough to cover expenses for full utilization of their ATCSs.

ATCS vendors and consultants need, on average, approximately 100 person-days to make an ATCS operational. However, this number also varies considerably among agencies. Some of the systems required as few as ten days to become operational, whereas others required as much as an entire year. In general, most ATCS users (80%) were satisfied with the technical support from vendors and consultants. Reasons not to be satisfied were primarily related to the costs of the technical support (32%) and that some ATCS vendors do not provide local expertise to some of the ATCS users (34%). The other major complaints were that ATCS consultants have only a few hands-on experts (often only one) who cover an entire nation or that the vendors were reluctant to modify or improve the ATCS to better fit the user's needs. Again, these problems can be associated with the number of ATCS users in the United States (or in the world). ATCS vendors and consultants do not find it profitable to train more than a few individuals on the ATCS or to customize software for a single user. If more agencies were to use ATCSs these problems would be expected to diminish.

Achievement of operational benefits from ATCSs is a major reason why these systems are installed. Outcomes of the following operational features are recognized as the most important benefits by ATCS users:

- Responds well to emergency vehicle preemption and traffic congestion resulting from crashes, clears backups quickly.
- Response to day-to-day and TOD fluctuations in demand.
- If traffic demand is light the cycle was lower and more accommodating.
- It does well when traffic flow is incremental, not when there are turbulent fluctuations in volume and demand.
- Coordination between signals, handling special events, changes in traffic volumes and patterns, and tourist area traffic.
- Ability to quickly respond to traffic fluctuations.
- Covers special sequence operations.
- Responds well to large volumes of traffic exiting on side streets that do not happen according to a regular schedule (e.g., a themed water park emptying as the result of a thunderstorm).
- Provides detailed information of traffic signal from central office.
- Maximizes throughput.
- Network control is delivered effortlessly.

On the other hand, the ATCS does not always perform as expected. There could be many reasons for this underperformance; at times, these systems are not fine-tuned and customized as needed. The literature review did not find any field evaluation studies that would show the benefits derived from the fine-tuning of an existing ATCS deployment. There have been few studies where suboptimal deployments of an ATCS are investigated (Taale et al. 1998; Jayakrishan et al. 2000); however, evaluations of customizing well-operated systems are rarely documented. With so many operational parameters that can be adjusted in everyday ATCS operations one would need to explore, if not to optimize, the values of those parameters to achieve optimal ATCS operations.

An ATCS sometimes does not perform as expected because initial expectations are set too high. When advertising an ATCS to potential customers, ATCS vendors at times overstate the abilities of these systems. This situation sometimes raises expectations concerning the ATCS, which in turn can lead to disappointment in their performance if the existing traffic problems cannot be solved (solely) by its deployment. Although the deployment of ATCSs can undoubtedly provide an improvement to traffic flows under normal (undersaturated) traffic conditions, it need not be considered a cure for capacity constraints. If the expectations for the system are too high, there is a chance that the system will not be perceived as successful. This is especially true when observed from a single traveler's perspective. The individual user's benefits of an ATCS (or any other system) are generally limited; however, when multiplied by the number of vehicles using the facility, they may bring significant savings to the motoring public. Surveyed ATCS users recognized the following operational issues:

- Poor operation for traffic demand surges such as those experienced during unplanned and planned special events.

- Synchronized phases sometimes get more green times than necessary, creating unnecessary delay on the other movements.
- System takes 5 to 10 s to respond to calls on minor phases—does not have detector switching.
- Single intersection falling off line.
- Poor split flexibility.
- System appears slower than expected when reacting to the variations of traffic flow and providing proper progression on the corridor.
- Construction activity—the detectors are either torn up, vehicles do not drive on them, or the lane is shut down and the detector senses that it is broken and goes into a "safe mode," causing problems.
- Pedestrian traffic—the system theoretically handles them well; however, our pedestrian volume is very high and pedestrian phases are needed during most cycles.
- Because we compromised, a stage-type controller is used, which limits the ability of the operation to a dual-ring configuration; only 30% of the ATCS features are being used.
- Not possible to identify a camera failure unless the intersection is monitored all the time.
- Data saving capacity—at present, data can be recalled only for the previous seven days.
- Does not handle rush hour volumes well owing to prediction horizon being too close.
- Emergency preemption and daily startup.
- Detection and communication failures.
- Handling oversaturated traffic conditions.
- Locked traffic flows—especially at roundabouts.

Some of the operational features are listed for both because they were handled well and/or not handled well by ATCSs. This discrepancy in the reported observations can be attributed to the knowledge that an ATCS of the same brand can function differently based on how it was set up and customized. There are also inherent differences in how various ATCS brands handle certain operational conditions. From the list of not-handled-well features one can observe several problems that indicate poor fine-tuning or customization of ATCS parameters (e.g., delay on minor movements or ATCS performance on corridors under construction). These problems do not necessarily indicate that the initial set up of the ATCS was poor, but that the system was not modified further, when changes in operational conditions warranted such a modification. An agency needs to fully understand operations of its ATCS to recognize that the system needs modification, even if the modification itself is done by an outside consultant.

MAINTENANCE

ATCS users find that, in general, ATCS components are more demanding with regard to maintenance than the comparable components used by conventional traffic control systems. Figure 6 shows how ATCS users perceive maintenance of major ATCS components (hardware, software, and communications). Sixteen percent of the ATCS users find that maintenance is much more demanding than with a regular system. Another 44% of respondents agreed that maintenance of ATCS is more demanding, but do not perceive such a large difference. Twenty-three percent found ATCSs to be similar to conven-

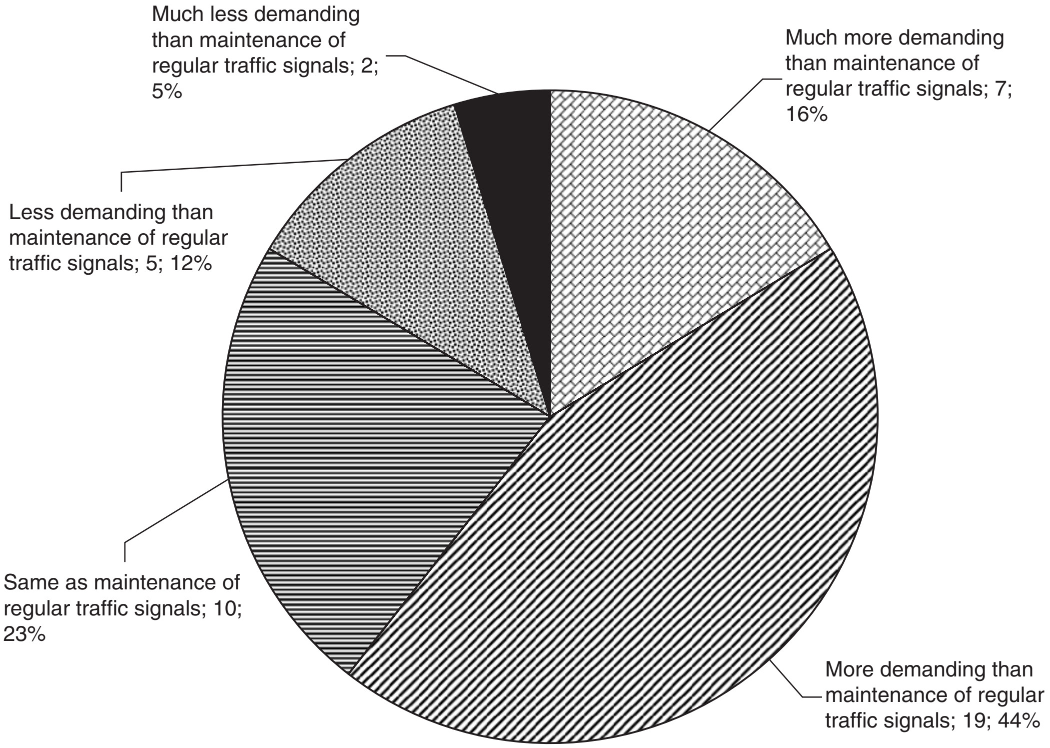


FIGURE 6 Level of difficulty of maintaining ATCSs.

tional traffic control in terms of the maintenance, whereas 17% believe that it is easier to maintain ATCSs than regular traffic signal systems. When it comes to which components of the systems are the most challenging to maintain, most of the ATCS users (65%) find that detection is the most challenging. The second and third most difficult components to maintain were found to be communications (30%) and software and hardware (11% each).

SUMMARY

This chapter identified institutional aspects of operations, training, and maintenance at the agencies that deploy ATCSs. ATCSs are only tools for traffic control, and as with any other tools could be supervised and controlled by a skilled engineering staff. Proper acquisition, training, and retention of expertise within an agency are the most important factors for alleviating institutional barriers for ATCS deployments. The current practice shows that at times an agencies' ability to fully master ATCS operations is not sufficient. ATCS operations are often not perceived as being difficult. However, it appears that there is a discrepancy between what ATCS users know and what they believe that they know about ATCS operations. Some agencies reported operational problems that indicated a lack of the basic knowledge on how to operate an ATCS despite survey results to the contrary. Most ATCS users rely on in-house expertise, which is more an indication of the lack of resources available to hire outside support than that ATCS agencies have the required expertise. Most of the agencies would prefer to acquire more expertise on the ATCS, but inadequate funding is the major obstacle to acquiring the required knowledge. Inadequate funding does not indicate only problems in getting proper training; more importantly, it limits an agencies' ability to hire more staff. Most of the ATCS users found that ATCSs are operationally more demanding than conventional traffic signal systems; however, overall, an agencies' ability to support these systems is less than to support conventional systems. The next chapter reports on system requirements for ATCS deployments.

CHAPTER FIVE

SYSTEM REQUIREMENTS

INTRODUCTION

There are many system requirements that define the quality of an ATCS, its deployment, and success. Even the best adaptive traffic control algorithms will not function properly if their operations are not supported by adequate hardware, software, communications, and system integration. This chapter identifies those system or operational requirements that are considered critical for ATCS operations. ATCS users were asked to describe their experiences with ATCS requirements. Their descriptions were captured through a set of questions regarding detection requirements, hardware, software, integration with legacy systems, and communications. In addition to discussing the agencies' practices, this chapter reviews some of the implementation problems and some lessons learned in practice.

DETECTION

Any traffic-responsive control system depends on its ability to detect traffic either for local intersection control or for network-wide adjustment of timing plans. ATCSs rely heavily on the quantity and quality of traffic data available from detectors. Poor or improperly installed detectors can affect ATCS performance, which can eventually lead to the removal of ATCS operations.

Historically, ATCS predominantly used inductive loops as a detection technology. Over the past several decades video detection has emerged as a cost-efficient and reliable replacement for the inductive loops. This trend was also observed in the analysis of the survey conducted for this project. Some of the ATCS agencies almost exclusively use video detection and are quite satisfied with its performance. On the other hand, some ATCS users overseas expressed reservations about the quality and reliability of video detection and exclusively use inductive loops. However, the survey showed that most of the agencies use a mixture of various detection technologies for their ATCS deployments. Although approximately 93% of the agencies use inductive loops, almost half (43%) also use video detection. Approximately 18% of the agencies use radar detection, whereas only 9% use other types of detection not contained in any of these three major technologies.

Detection coverage is very important for the success of an ATCS. One of the most significant barriers for widespread deployment of ATCSs is a notion that such a system requires much more detectorization than conventional traffic-actuated signal systems.

Responding agencies reported that their ATCSs utilize anywhere from 4 to 24 detectors (8 to 12 detectors on average) to cover a single four-leg intersection with one through lane and two turning bays (left and right) for each leg. Although these results might be viewed with some caution, because various agencies deploy detectors differently for their traffic-actuated operations, the findings do not fully support the notion that ATCSs require much more detection coverage than operations of traffic-actuated signal systems.

Various ATCSs use a combination of detection layouts to estimate the current state of traffic, which is later used to adjust traffic control in a network. There are generally four major detector locations used by most ATCSs:

- Stop-line detectors (e.g., as seen in common actuated operations in the United States and SCATS).
- Upstream detectors located close to the stop-line (10–15 m), which cannot be used (owing to their proximity to the stop-line) to easily estimate queue length (e.g., as used in Germany by BALANCE and MOTION).
- Upstream (mid-block) detectors, which can be used to estimate reasonably long queue lengths (e.g., as seen at some Californian intersections and used by ACS Lite).
- Upstream (far-side) detectors located at the exit point of the upstream intersection (as used by SCOOT, UTOPIA, and optionally by RHODES).

Detection layout used by an ATCS correlates with the adaptive control logic that is used to adjust signal timings for the prevailing traffic conditions. Sometimes detection layout is established to provide good measures for the adaptive control logic [e.g., in SCOOT—upstream detectors selected to accommodate for Traffic Network Study Tool (TRANSYT) logic]. Other times, adaptive traffic control logic is developed for the existing detection layouts (e.g., SCATS logic for stop-line detectors).

When asked which of the four detection types they use, the responding agencies were not able to make a clear distinction between mid-block and upstream detectors on one side and stop-line and near stop-line detection on the other side. Therefore, aggregated results were provided for these two major detection placement categories. Approximately 42% of interviewed agencies reported that their systems use upstream detection. Distance between these detectors and the downstream intersection varies anywhere from 10 to almost 300 m (40 to 800 ft). On the other hand, approximately 50% of the respondent's ATCSs use stop-line detection exclusively. The rest of the respondents (approximately 8%) use various combinations of the upstream and stop-line detection in their ATCS operations.

Left-turn detection is handled by 50% of the interviewed agencies at stop-lines. The other 50% of the respondents use upstream detection for left-turn movements, but a wide variety of solutions is applied. Some agencies use common (for the United States) queue detectors located two to three car lengths behind the stop bars, whereas others use combinations of upstream detectors and filter detectors based on the local conditions at each left-turn movement. Placement of the upstream left-turn detectors varies from approximately 20 m (50 ft) to the full length of the left-turn bay. Filter detectors are usually not placed in the storage bay of the left-turn movement but in the through exiting lane of the intersection leg that receives left-turn traffic.

Depending on the sensitivity of ATCS operations on detection inputs, the system may have more or less significant problems when certain detectors fail. ATCSs that are less sensitive to short-term inputs from detectors tend to be more robust and work better when minor detection failures occur. However, these ATCSs may sometimes be insensitive to the changes in traffic flows. Most of the ATCSs provide some features that allow for replacement of the missing detection data using historic traffic records. Therefore, if a certain detector fails, the system finds and uses data from the respective day and time of day, which will approximate current operations. Such ATCS use of historic traffic data may reduce the impact of the detector malfunction on overall performance of the ATCS.

Minor detector failures are relatively frequent events in everyday ATCS operations. Although these minor failures may have a significant impact on ATCS performance (e.g., detectors for a major signal group fail at the critical intersection), their impact is usually limited. Low impact of minor detection failures on overall operations may not trigger a quick response from the agency and detection repair time might be prolonged. For this reason, it is important to find out how major ATCS users perceive the quality of ATCS operations during the minor (by its scope) detection problems. The results from the survey are shown in Figure 7. Fewer than 20% of interviewed ATCS users reported that their systems perform poorly (or very poorly) during the minor detection problems.

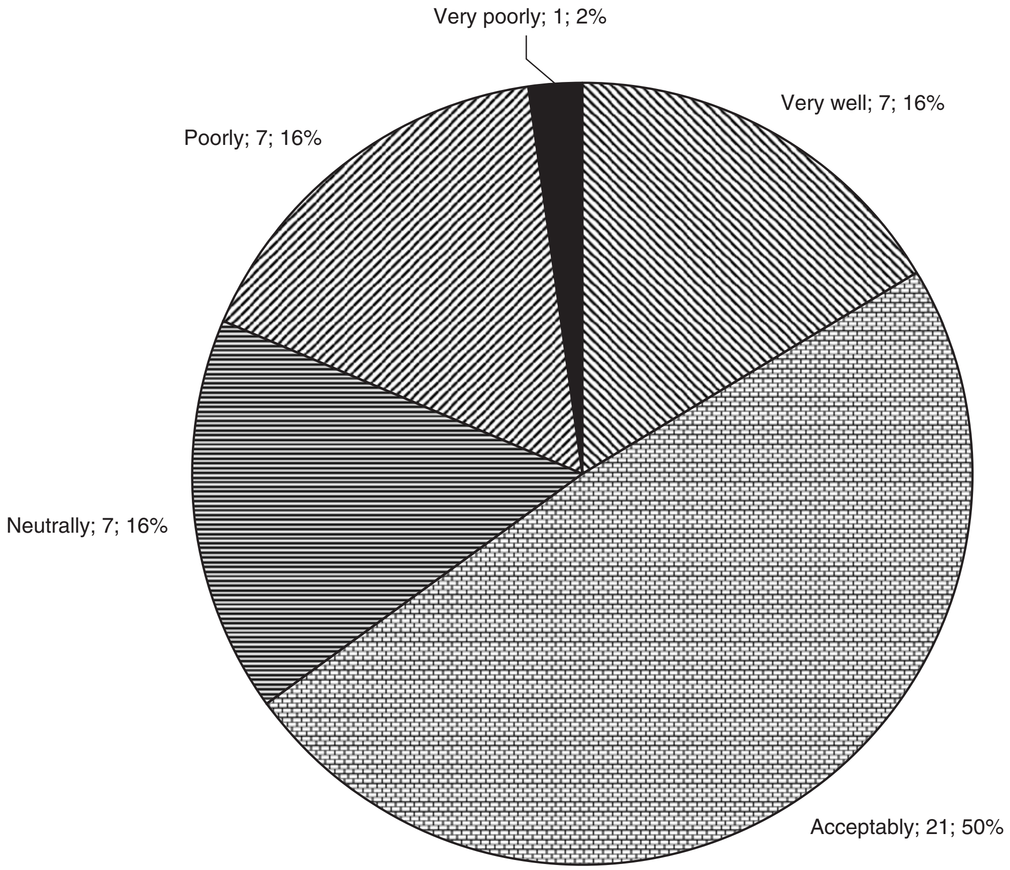


FIGURE 7 ATCS operations with minor detection malfunction.

Major detection failures degrade ATCS operational performance. Under such conditions, an ATCS may continue to work as if nothing happened, and in the best case scenario it will work based on the historic data or as an actuated-coordinated traffic signal system. If the background actuated-traffic operations are designed properly the system may continue to work for hours or days before any operational change is noticed. For this reason it is important that ATCSs have the ability to alert operators about major detection failures. Although most ATCSs have such ability, 16% of ATCS users reported that their system continues to operate as if nothing happened, without notifying the operators about detector malfunction. Approximately 53% of the ATCS users reported that detector malfunction triggers an alarm and notifies the operators. When it comes to "safe mode" operations during the major detection failure, 26% of ATCS users indicated that their systems switch to off-line TOD operations, whereas approximately 25% answered that their ATCS start using historic traffic profiles.

HARDWARE

ATCSs are usually installed when agencies are ready to radically change traffic signal operations on arterial networks. Usually such changes include the replacement of existing local intersection hardware (i.e., controllers or controllers and cabinets) that may be reaching the upper end of its anticipated life span. However, installation of the hardware necessary to operate an ATCS usually involves installation of components not familiar to the local agency's staff. Therefore, the problems that may arise with new hardware have two components: (1) technical (quality of the hardware components) and (2) institutional (training necessary to master operations of new hardware).

If the central hardware and local controllers do not meet ATCS requirements, system performance will suffer. In the past, some of the ATCS deployments in the United States were shut down because of the problems with local traffic controller or central system hardware. Incompatibility of imported local controllers (previously required for operations of some international ATCSs), problems with communication between the controller's unit and coprocessor card, and uncommon central hardware are only some of the examples of such hardware problems. Table 9 shows which traffic controller types are most commonly used by U.S. agencies. International agencies that deploy ATCSs mostly use controllers that run their local controller standards (i.e., Novax controllers in Canada, SCATS controllers in Australia, etc.).

Approximately 80% of interviewed agencies reported that they are familiar with the hardware that their ATCSs use. The 20% who reported that they were not completely familiar with the hardware emphasized the following problems:

- Special protocol modifications were made to support existing hardware [i.e., Virtual Machine Environment (VME) processor cards, second central processing unit in 2070 controller],
- New hardware components (digis, modems, interfaces) were not used before by the agency ("black box" syndrome), and
- Training was necessary for field technicians to learn how to use new controllers and other hardware.

SOFTWARE

Another key component in operations of an ATCS is the friendliness (interoperability and usability) of the ATCS software. In a category of questions that addresses this topic, ATCS users were asked to provide information about the operating systems and platforms of their systems, as well as the integration of their systems with Advanced Traffic Management Systems (ATMS).

Windows-based operating systems are used at approximately 57% of the interviewed agencies. Ten percent of ATCS users run their systems on Unix-based operating systems. Open VMS, an operating system mostly used as a SCOOT platform, was reported by 14% of the interviewed agencies. It is interesting to note that only 14% of ATCS users reported using an Open VMS operating system. Considering that almost 35% of the interviewed agencies use SCOOT systems, which almost unanimously still run on Open VMS (there are only few installations in the world where SCOOT runs on a Windows-based platform), the results indicate that some of the ATCS users are not sufficiently familiar with their ATCS.

When asked how user-friendly they consider their ATCS software, only 18% of the interviewed agencies responded that their system's software is very friendly. Results from this part of the survey are presented in Figure 8 and they show that ATCS software generally keeps up with users' expectations. However, almost one-half of the ATCS users are not very satisfied with the way their ATCS software works. Software development is a time-consuming and costly process. Unlike common Windows-based applications (e.g., MS Office) ATCS software is developed for (and sold to) a couple of hundred users (at most) around the world. Also, each ATCS deployment is somewhat unique (various hardware and soft-

TABLE 9
TYPES OF TRAFFIC CONTROLLERS USED BY ATCS

Traffic Controller Type	Percent of Agencies
NEMA TS-1	30
NEMA TS-2	35
2070 ATC	34
Model 170	1

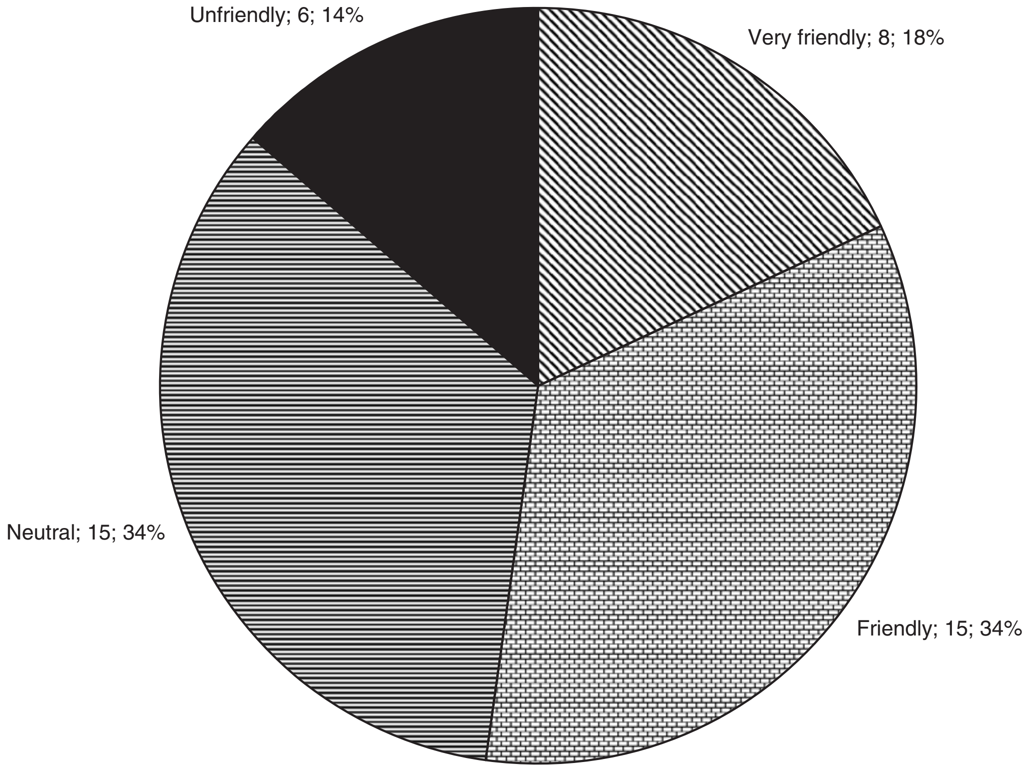


FIGURE 8 Friendliness of ATCS' software.

ware elements need to be integrated), which sometimes requires software customization that is beyond the financial support allocated for ATCS deployment. Under such circumstances it is understandable that ATCS software does not always keep pace with modern software developments and therefore may appear somewhat archaic to ATCS users. With an increase in the size of the base of ATCS users it is expected that the gap between ATCS software and general software trends will decrease.

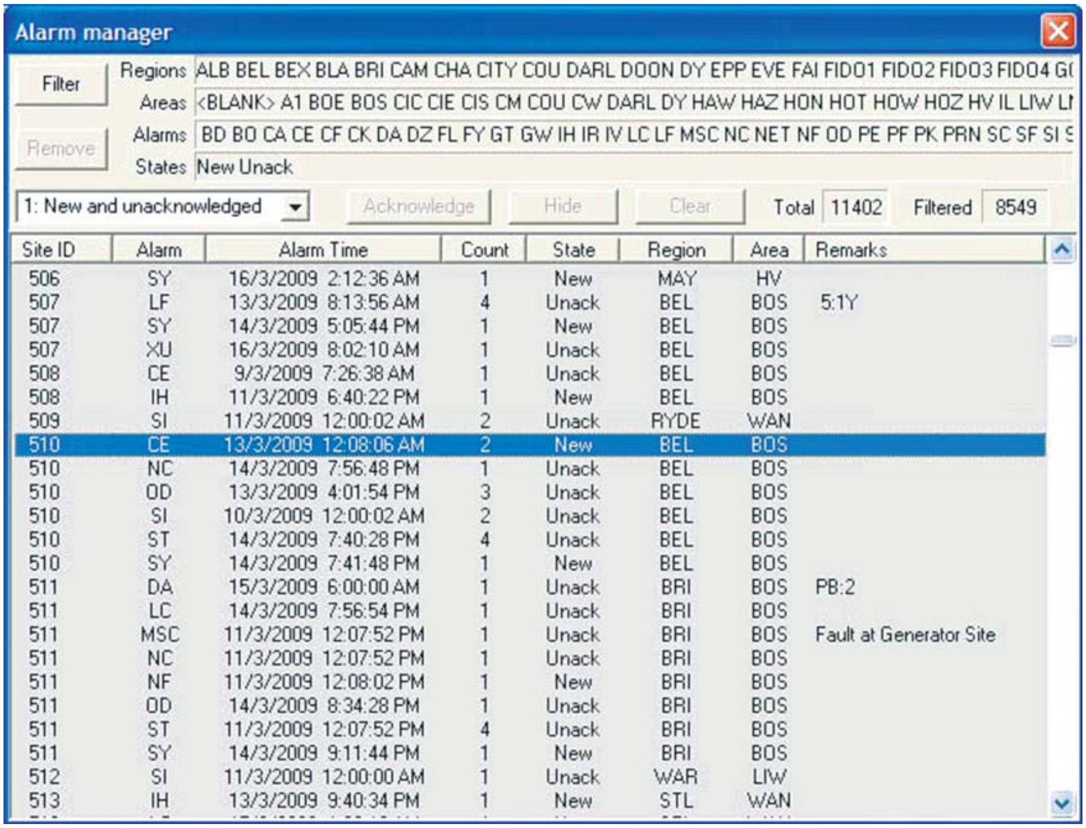
Although ATCSs can independently control traffic signals they are often integrated with an ATMS, which is used to manage the traffic signal system, providing such functions as Graphical User Interface, archived database management, and a graphic display system showing signal status, operating effectiveness, and communications. The ATMS provides integrated control of a variety of surface street traffic management functions, including traffic signals, dynamic message signs, closed-circuit television (CCTV) cameras, and vehicle detection. If an agency runs an ATMS and wants to deploy ATCS (or vice versa) it is often important that these two tools are integrated or interoperable in order to deliver improvements associated with both systems. However, such integration can be very difficult to execute, owing to a number of reasons such as costs, intellectual rights, etc., and is rarely performed. However, some of the ATMSs are preprogrammed to offer integration with certain ATCSs, in which case an ATCS runs as a single option among various traffic control platforms within the ATMS [e.g., ACTRA—SCOOT, Management Information System for Transportation (MIST)—OPAC].

Results from the survey showed that 21% of ATCS users do not have an ATMS. Seventeen percent of those users who do have an ATMS do not have their ATCS and ATMS interfaced. Those ATMSs that are the most frequently used are ACTRA, MIST, and i2TMS with 10%, 10%, and 7% of ATCS users, respectively. Approximately 48% of interviewed ATCS users utilize other ATMS (T2000C, Aries, Sitraffic, Alcatel ATM, TMIS, etc.).

One of the major ATCS software functions is to report malfunctions and other diagnostics of its hardware and software components. ATCS Graphical User Interfaces usually provide a full range of operator commands and monitoring functions. Some of the typically displayed data for monitoring operations at an intersection are:

- Lamps on/off/flashing
- Current phase demands
- Detectors occupied
- Current cycle time
- Operating mode
- Alarms
- Current phase
- Elapsed phase time.

Most of the interviewed ATCS users (95%) reported that their ATCSs are capable of reporting necessary diagnostics. Figure 9 shows how system alarms are logged, viewed, and managed in SCATS' Alarm Manager. Equally important parameters that need monitoring are operational



Regions ALB BEL BEX BLA BRI CAM CHA CITY COU DARL DOON DY EPP EVE FAI FIDO1 FIDO2 FIDO3 FIDO4
Areas <BLANK> A1 BOE BOS CIC CIE CIS CM COU CW DARL DY HAW HAZ HON HOT HOW HOZ HV IL LIW
Alarms BD BO CA CE CF CK DA DZ FL FY GT GW IH IR IV LC LF MSC NC NET NF OD PE PF PK PRN SC SF SI
States New Unack
1: New and unacknowledged
Total 11402
Filtered 8549

Site ID	Alarm	Alarm Time	Count	State	Region	Area	Remarks
506	SY	16/3/2009 2:12:36 AM	1	New	MAY	HV	
507	LF	13/3/2009 8:13:56 AM	4	Unack	BEL	BOS	5:1Y
507	SY	14/3/2009 5:05:44 PM	1	New	BEL	BOS	
507	XU	16/3/2009 8:02:10 AM	1	Unack	BEL	BOS	
508	CE	9/3/2009 7:26:38 AM	1	Unack	BEL	BOS	
508	IH	11/3/2009 6:40:22 PM	1	New	BEL	BOS	
509	SI	11/3/2009 12:00:02 AM	2	Unack	RYDE	WAN	
510	CE	13/3/2009 12:08:06 AM	2	New	BEL	BOS	
510	NC	14/3/2009 7:56:48 PM	1	Unack	BEL	BOS	
510	OD	13/3/2009 4:01:54 PM	3	Unack	BEL	BOS	
510	SI	10/3/2009 12:00:02 AM	2	Unack	BEL	BOS	
510	ST	14/3/2009 7:40:28 PM	4	Unack	BEL	BOS	
510	SY	14/3/2009 7:41:48 PM	1	New	BEL	BOS	
511	DA	15/3/2009 6:00:00 AM	1	Unack	BRI	BOS	PB:2
511	LC	14/3/2009 7:56:54 PM	1	Unack	BRI	BOS	
511	MSC	11/3/2009 12:07:52 PM	1	Unack	BRI	BOS	Fault at Generator Site
511	NC	11/3/2009 12:07:52 PM	1	Unack	BRI	BOS	
511	NF	11/3/2009 12:08:02 PM	1	New	BRI	BOS	
511	OD	14/3/2009 8:34:28 PM	1	Unack	BRI	BOS	
511	ST	11/3/2009 12:07:52 PM	4	Unack	BRI	BOS	
511	SY	14/3/2009 9:11:44 PM	1	New	BRI	BOS	
512	SI	11/3/2009 12:00:00 AM	1	Unack	WAR	LIW	
513	IH	13/3/2009 9:40:34 PM	1	New	STL	WAN	

FIGURE 9 Alarm manager in SCATS.

traffic parameters, which help ATCS operators to monitor the quality of the executed signal timing plans and dynamical changes in traffic conditions. All of the ATCSs provide tools and functionalities to monitor and track variations of operational traffic parameters. Figure 10 shows a Dynamic Map functionality supported by the LA DOT's ATCS, where a set of traffic performance measures (such as volume, speed, queue, stops, and delay) are reported dynamically in real time. These and similar traffic performance measures from other ATCSs can be archived in system databases for future use. ATCS users find this functionality, of archiving traffic metrics, very useful. Only 17% of the interviewed ATCS users do not believe that reported traffic performance measures are useful for other traffic engineering purposes.

ADAPTIVE TRAFFIC CONTROL SYSTEMS AND MICROSIMULATION TOOLS

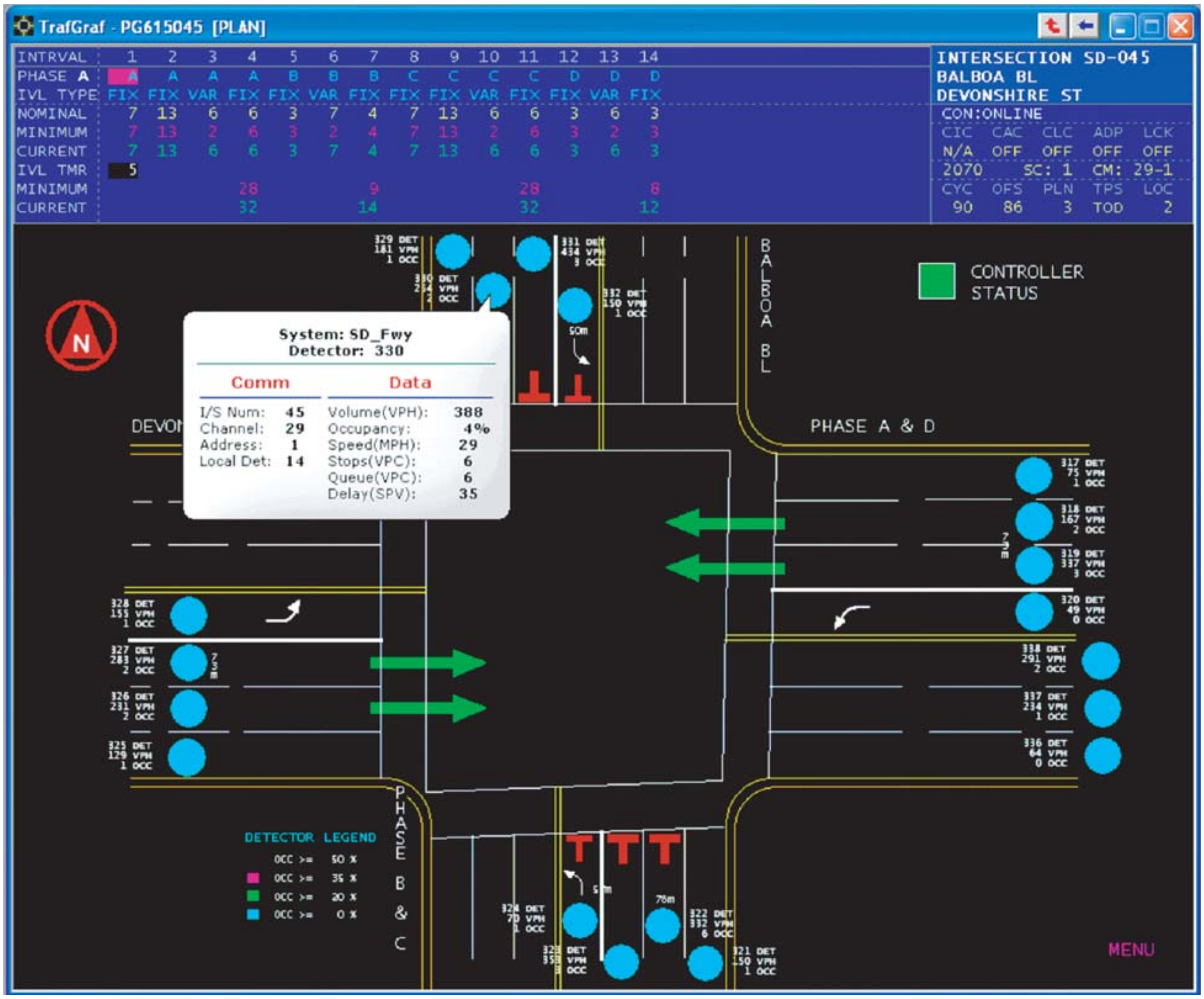
A major disadvantage of field ATCS evaluations, reported through survey response and in the literature, is that these evaluations always require an ATCS to be installed and, as such, they represent post-deployment justification studies. Also, as a result of costly field data collections, these evaluations are not practical for the investigation of the long-term benefits of ATCS deployments. To address these issues traffic signal researchers and practitioners have interfaced traffic microsimulation tools to ATCS software. Studies where microsimulation, coupled with an ATCS, is used to evaluate the effectiveness of an ATCS before its field installation are very rare. The lack of pre-installation evaluations of ATCSs through microsimulation can be attributed to three major factors:

- A lack of confidence in microsimulation results, which is still present among many traffic engineers and decision makers.
- The complexity and costs of modeling field conditions in microsimulation and interfacing the microsimulation model to an ATCS software.
- The costs and institutional issues (licensing) associated with acquiring ATCS software to be tested and/or evaluated in microsimulation.

In spite of these limiting factors almost all ATCSs have been interfaced with certain microsimulation tools. Discussion of these interfaces and relevant research studies is beyond the scope of this report. A reader is advised to review the bibliography section in Appendix C for further information on the most important studies regarding ATCS modeling in microsimulation. Table 10 shows microsimulation tools that have been coupled with the ATCSs described in this report.

COMMUNICATIONS

The importance and costs of communications that are necessary to provide reliable ATCS operations primarily depend on the way in which signals are interconnected in ATCS network



TrafGraf - PG615045 [PLAN]

INTRVAL	1	2	3	4	5	6	7	8	9	10	11	12	13	14
PHASE **A**	A	A	A	A	B	B	B	C	C	C	C	D	D	D
IVL TYPE	FIX	FIX	VAR	FIX	FIX	VAR	FIX	FIX	FIX	VAR	FIX	FIX	VAR	FIX
NOMINAL	7	13	6	6	3	7	4	7	13	6	6	3	6	3
MINIMUM	7	13	2	6	3	2	4	7	13	2	6	3	2	3
CURRENT	7	13	6	6	3	7	4	7	13	6	6	3	6	3
IVL TMR	5													
MINIMUM				28			9				28			8
CURRENT				32			14				32			12

INTERSECTION SD-045
BALBOA BL
DEVONSHIRE ST

CON:ONLINE

CIC	CAC	CLC	ADP	LCK
N/A	OFF	OFF	OFF	OFF

2070 SC: 1 CM: 29-1

CYC	OFS	PLN	TPS	LOC
90	86	3	TOD	2

System: SD_Fwy
Detector: 330

Comm		Data	
I/S Num:	45	Volume(VPH):	388
Channel:	29	Occupancy:	4%
Address:	1	Speed(MPH):	29
Local Det:	14	Stops(VPC):	6
		Queue(VPC):	6
		Delay(SPV):	35

FIGURE 10 Dynamic map in LA DOT ATCS.

architecture. For distributed systems, in which the intersection controller is responsible for control, communications between hardware elements at the intersections are the most important. In distributed systems there is no need for a reliable communications network between intersections and a central system. Consequently, inexpensive communications alternatives, including wireless alternatives, are viable options. The savings in communications infrastructure usually compensates for the potential higher cost of local controllers. Distributed systems typically cost between $10,000 and $30,000 per intersection (Malek et al. 1997).

TABLE 10
AVAILABLE INTERFACES BETWEEN ATCS AND MICROSIMULATION TOOLS

ATCS	Microsimulation Tool
ACS Lite	CORSIM, VISSIM
BALANCE	NONSTOP, VISSIM
InSync	VISSIM
LA ATCS	CORSIM (offline post-processing interface)
MOTION	VISSIM
OPAC	CORSIM
RHODES	CORSIM, Q-Paramics
SCATS	S-Paramics, VISSIM, AimSun
SCOOT	VISSIM, CORSIM, S-Paramics, AimSun
UTOPIA	VISSIM, AimSun, S-Paramics

Only 9% of interviewed ATCS users find peer-to-peer communications to be the most important type of communications for their systems. Another 9% put peer-to-peer communications as second in order of importance. Finally, 44% of ATCS users do not believe that peer-to-peer communications are important for their systems.

In centralized systems, a central computer makes control decisions and directs the actions of individual controllers. These systems depend on reliable communications networks. Because real-time control commands are transmitted from the central computer to the local intersection, any interruption in the communications network forces the local controller to operate without that real-time control and revert to its backup plan, which usually is time-based coordination; however, this

TABLE 11
COMMUNICATIONS BETWEEN CENTRAL AND LOCAL ENTITIES IN ATCS

Criticality of Communications Between Central System and Local Controllers	Percent of Agencies
Critically important	62
Somewhat important	15
Not important	23

still requires a transition from central control to local control. During this transition, signal coordination is usually lost for a short period of time. For this reason, communications networks for centralized systems most often include some form of fixed communications, with most agencies preferring to own their infrastructure. These communications media include twisted-pair copper wire and fiber-optic cable. The physical media typically provide inherent reliability of 99.995% to 99.99995%, with downtime ranging from a few seconds to a few minutes a year. In real systems, downtime is much higher because of physical intrusion on the infrastructure, though some fiber network approaches even minimize the effects of that danger. Communications networks for centralized systems typically consume at least two-thirds of the cost of a system. Centrally controlled systems usually cost between $40,000 and $80,000 per intersection (Malek et al. 1997). Table 11 shows how interviewed ATCS users perceive criticality of communications between their central systems (if any) and field local controllers.

Although the users of distributed ATCSs value peer-to-peer and local-to-central communications differently from those users who use centralized ATCSs, all were expected to give equal importance to communications between various elements at the intersection. Results show that communication between various elements at the intersection is consistently placed as second in importance, with 50% of users selecting that choice. Eighteen percent of respondents give the highest importance to this type of communication, whereas 32% of the respondents did not report this as being important.

Figure 11 shows that approximately 80% of all ATCS agencies use three major types of communication media (twisted pair, telephone lines, and fiber optic cables) to communicate between the central system and field controllers. These results can be explained by noting that ATCSs that need central-system-to-field-controller communication require very reliable communication for their ATCS operations, which is ensured through the use of physical media between various elements in their ATCS architecture.

According to the survey respondents, a similar share of various media types is observed for peer-to-peer communication

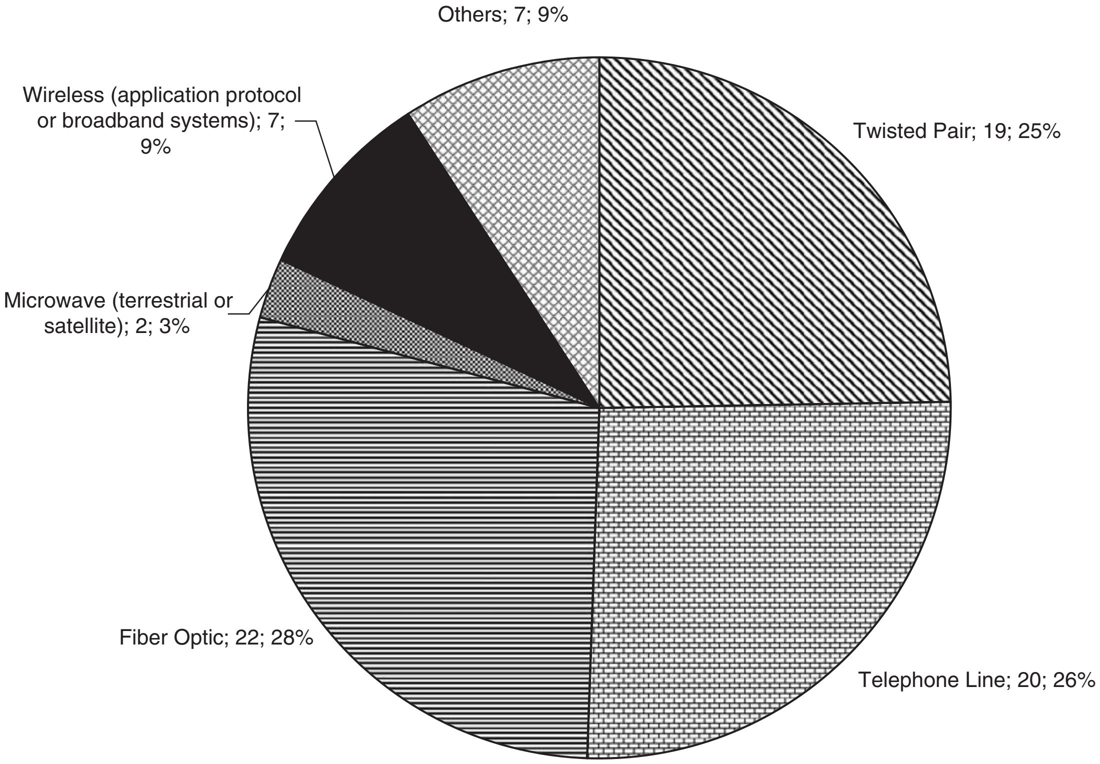


FIGURE 11 Communication media between central system and field controllers.

TABLE 12
MEDIA FOR PEER-TO-PEER COMMUNICATION

Communication Media	Percent of Agencies
Twisted pair	43
Fiber optic	41
Telephone line	20
Wireless	7
Microwave	2
Other media	5
Does not need any peer- to-peer communications	16

Note: Total percentage exceeds 100 because some of the interviewed agencies deploy multiple types of communication media at various intersections under their jurisdiction.

in ATCS operations. Table 12 shows the percentages of various media types used by interviewed ATCS users for their peer-to-peer communications.

Overall, ATCS users do not find that communications for their ATCSs are much more demanding than communications for conventional traffic control systems. The majority of the respondents (72%) find that their communications for ATCSs function similar to other traffic control systems. Sixteen percent of the respondents indicated that they have more problems with communications for the ATCS than with communications for their regular systems, whereas 12% of the respondents believe that the opposite is the case.

SUMMARY

This chapter identified system requirements for ATCSs and described how ATCS users perceive those requirements. Detection requirements for ATCSs remain slightly higher than those for conventional traffic-actuated control systems. Most of the ATCS users are satisfied with the way their system handles minor detector malfunctions and reports the major detector malfunctions. Early problems with ATCS hardware, which was incompatible for local controllers (primarily for early installations of international ATCSs), are mostly gone. ATCS users still sometimes struggle with handling ATCS-specific hardware primarily owing to a lack of operational knowledge, which in turn indicates a lack of proper training. Although most of the users find their ATCS software to be user-friendly, there is a notion that the friendliness of the software can be significantly improved. Most of the ATCS users do not find that ATCS communications cause more problems than the communications of conventional traffic control systems. Still, communications costs are one of the major operational costs for ATCS users and communications problems may take significant amounts of their time and resources. The next chapter reports on the implementation costs and benefits of ATCS deployments.

CHAPTER SIX

IMPLEMENTATION COSTS AND BENEFITS

INTRODUCTION

Many factors influence the costs of an ATCS deployment and achievement of the full ATCS benefits. This chapter identifies those factors that affect the costs of installing and operating ATCSs. The chapter also addresses users' expectations and achieved benefits from the ATCS deployments. The costs of ATCS deployments are captured through the costs of system installations per intersection and comparison of maintenance costs for ATCSs and non-ATCSs. In addition to discussing the common evaluation studies to investigate the performance of ATCSs, this chapter reviews the benefits of various ATCS deployments. Finally, the chapter addresses public perception on ATCS implementations and provides some examples of lessons learned in practice during the implementation of ATCSs.

COSTS OF DEPLOYING ADAPTIVE TRAFFIC CONTROL SYSTEMS

According to an earlier study (Hicks and Carter 2000), cost appears to be a major obstacle to widespread ATCS deployment. The term cost here encompasses both the capital and the operations and maintenance costs of an ATCS. There is some disagreement whether over the long term ATCSs are more cost-effective than traditional signal systems because ATCS operations and maintenance costs are much lower than those associated with signal re-timing. Others argue that the estimates need not be simplified because an ATCS may have higher costs of physical maintenance such as the repair and replacement of detector loops. However, the answer, as always, lies somewhere in between. There are ATCSs that do not experience higher detection maintenance costs than conventional traffic signal systems. Conversely, some ATCSs may have significant signal timing adjustment costs. Belief that ATCSs do not require any fine-tuning and that they can self-adjust their operations indefinitely is one of the biggest myths about these systems.

A review of some recent ATCS deployments show that licensing costs to run such a system may contribute an additional 10% to 15% to the overall installation costs. The licensing costs are usually not one-time costs because the licensing rights are sold separately for various intersection bundles. If an agency wants to expand the system it will likely need to purchase licensing rights for a larger intersection bundle. Although there was a indication that licensing costs for system expansion are too high, only 42% of all interviewed ATCS users agreed with this notion. Approximately 38% of the respondents found the licensing costs for the expansion of their systems to be affordable, whereas approximately 20% either do not have to pay any licensing fees or did not need to expand the systems and do not know what the licensing expansion costs would be.

On average, the costs of installing an ATCS are approximately $65,000 per intersection. Figure 12 is a histogram of ATCS installation costs per intersection. The histogram shows that these costs can vary significantly among various ATCS users. The median and mode of the distribution (of ATCS installation costs per intersection) are approximately $45,000 and $40,000, respectively. These numbers are significantly higher than estimates reported previously in the literature (Hicks and Carter 2000), where similar estimates were between $20,000 and $25,000. It is important to note here that the reported costs often include more than just the installation of the adaptive component of the system. Replacements of the local intersection hardware and software (sometimes even installation of new communication infrastructure) often accompany installation of the adaptive algorithms. In spite of the survey's attempt to separate pure ATCS installation costs from the infrastructure upgrade costs, which do not necessarily need to be conducted at the time of ATCS installation, the ATCS users were able to report only the total costs (per intersection) of their system deployments.

Once an ATCS is installed there are costs to operate and maintain both the hardware and software of the system, as well as the infrastructure whose maintenance may be more costly owing to the higher infrastructure needs required by an ATCS operation (e.g., more detectors or newer communications). The percentage of an agency's annual budget that is spent on the physical maintenance of an ATCS is a good indicator of the cost-efficiency of maintaining these systems. To get an unbiased picture of the costs of ATCS maintenance we need to consider also the percentage of intersections that run under an ATCS. Figure 13 shows the correlation between the two percentages. The figure indicates that, in general, proportions of annual budgets that are spent on maintaining an ATCS are lower than proportions of intersections under the ATCS in the total number of intersections. The few outliers that were originally in the data set were removed to achieve a better coefficient of determination (R^2). Removal of the outliers did not change the overall relationship between *X* and *Y* data sets;

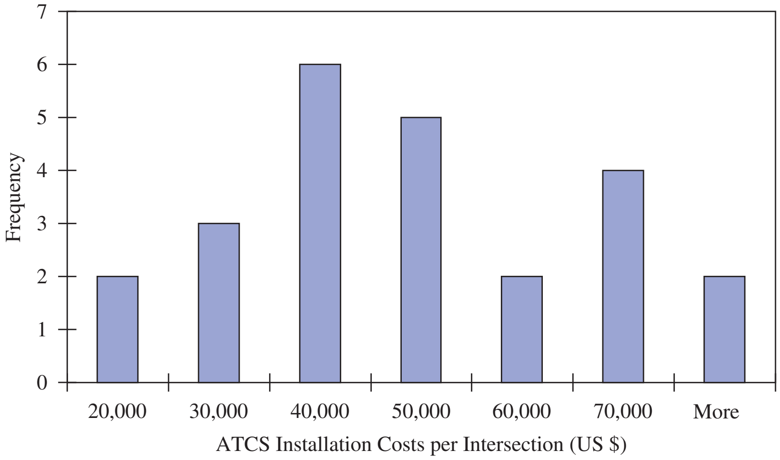


FIGURE 12 Histogram of ATCS installation costs.

however, the scatter of the data points is reduced. This chart shows that when it comes to the costs of the physical maintenance, ATCSs are more efficient than conventional traffic signal systems, which is the opposite of a widely accepted notion that ATCSs are expensive to maintain (especially communications and detection).

The other components of costs for maintaining an ATCS operation include consulting costs and the costs of maintaining ATCS hardware and software. Although there is a notion that once an ATCS is set up there is no need for re-timing traffic signal timing plans, there are some costs of reconfiguring ATCS parameters. These costs can be significant owing to inadequate in-house expertise to adjust ATCS parameters to meet new operational needs. Most ATCS agencies have difficulties comparing estimates for the per-intersection annual costs of maintaining optimal signal timings (e.g., consulting, hardware, and software costs) for ATCS and non-ATCS signals. A variety of answers were collected from respondents: from costs of maintaining an ATCS being 10 times lower than a non-ATCS costs to non-ATCS costs being 4 times lower than ATCS costs. On average, the ATCS agencies found that maintaining "optimal" signal timings under an ATCS accounts for only 75% of what is spent to maintain comparable signal timings under non-ATCS signals.

EVALUATION STUDIES

Evaluation studies that compare the effectiveness of a pre-ATCS traffic signal system with the effectiveness of the ATCS usually follow any new ATCS deployment. Most of the time (in 53% of the cases) ATCS users hire outside consultants to measure improvements in traffic operations

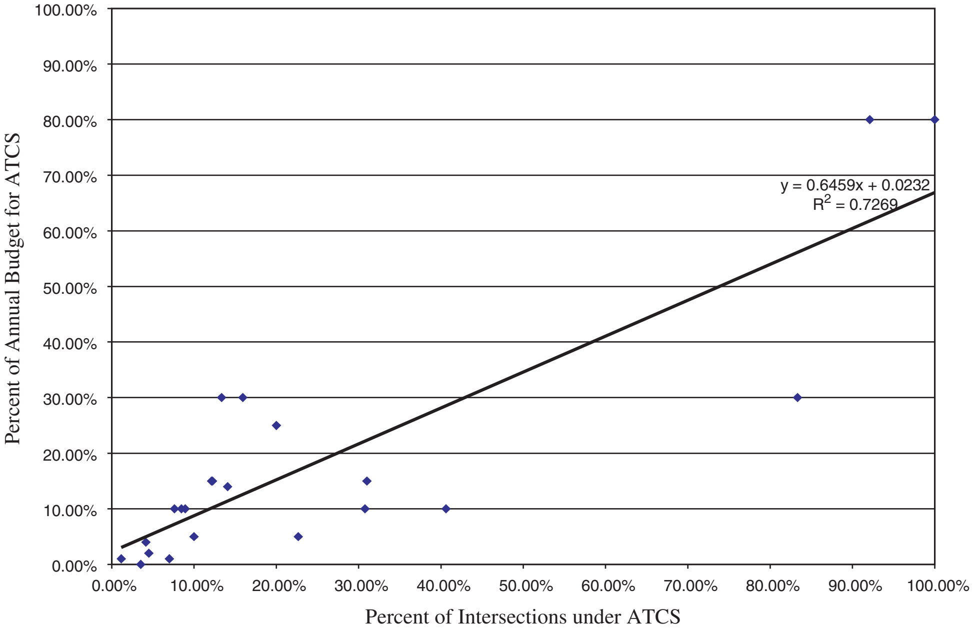


FIGURE 13 Correlation between ATCS shares in budget and operations.

gained by the implementation of an ATCS. All other times (33%), these studies are done in-house by the ATCS agencies. Fourteen percent of the interviewed agencies never performed any evaluations to investigate the benefits of their ATCS deployment.

ATCS evaluation studies are done either in the field or by using high-fidelity microsimulation models. Commonly, field evaluations are done as a set of before-and-after studies where the "before" study reflects field conditions with pre-ATCS traffic signal control and the "after" study reflects the performance of an ATCS. Before-and-after studies are done to compare all sorts of alternatives that can possibly bring benefits to traffic operations. When a new ATCS is deployed, this comparison of old versus new traffic control strategies may have another dimension. If an ATCS is installed with the ability to implement various signal timing plans, evaluators of the new system can re-apply the old traffic control timings in the new conditions for the sake of a fair comparison of the two (new and old) traffic control strategies. Most ATCSs have the ability to turn off their adaptive control algorithms and implement the TOD signal timings that were in effect before the ATCS was installed. In this way, both old and new traffic control strategies are exposed to (approximately) the same traffic conditions, as opposed to the before-and-after study where traffic conditions could significantly change between completions of these studies. This approach to evaluating new and old traffic control is often called an Off versus On study. Off here refers to new traffic control being switched off (and instead running old TOD plans) and On refers to new traffic control being implemented.

Field evaluations of ATCSs have their limitations. The experimental designs of such evaluations often lack rigor because of idiosyncratic traffic patterns that are difficult to control. However, no less difficult are the requisites for validating simulation models that also depend on field conditions. Field data collection is expensive and usually cannot be as comprehensive as simulation outputs even with extensive survey instrumentation. Field evaluations typically address limited sets of traffic conditions. Furthermore, unexpected traffic conditions are by their very definition tough to capture; however, ATCSs are known for providing good performance in such circumstances. When an installation deviates from the requirements owing to a compromise by the client agency or inadequate maintenance, the ATCS is then subject to an unfair comparison.

ATCS evaluations through microsimulation overcome these shortcomings. Traffic conditions can be controlled tightly; they can be replicated and varied stochastically. Incident-and event-based traffic conditions can be constructed and tested carefully. Installation can be simulated to be optimal with high-quality detector placement and rigorous management of global and local control parameters, such as timing constraints. However, field evaluations exceed microsimulation evaluations in other aspects. For instance, there is always a margin between microsimulation and reality. Data communication between the ATCS kernel, local traffic controllers, and traffic detectors has to be emulated, which may be a difficult task.

Survey results show that field evaluations are still the major way of evaluating ATCSs. Table 13 shows how popular various evaluation studies are with ATCS users. "On and off" studies refer to evaluations where ATCSs are tested with full adaptive logics turned on and then turned off (with TOD plans running in the background).

When performances of an ATCS and a non-ATCS traffic signal system are comparatively evaluated a variety of performance measures can be compared. Figure 14 shows the most common performance measures in such evaluations. The leading performance measure is travel time (or travel delay along the travel time segment) followed by the number of stops, intersection delays, average speeds, and queue lengths, in that order.

BENEFITS FROM ADAPTIVE TRAFFIC CONTROL SYSTEMS DEPLOYMENTS

ATCSs are known to have several advantages over traditional traffic signal timing operations with TOD plans. Ideally, ATCSs work best in conditions with high levels of nonrecurring congestion, such as incidents and special events, and in areas with fluctuating traffic demand. As mentioned earlier, an ATCS is not necessarily "the answer" for any situation. It is important to understand that it should not be expected that an ATCS deployment can totally resolve all traffic congestion issues. Instead, ATCSs could be considered as tools that can help to reduce traffic congestion by promoting the operational control and management of the transportation network. The primary area of benefits that can be achieved by an ATCS deployment is operational efficiency, measured through the reduction of delays, stops, and other negative measures of traffic performance. ATCS deployment improves the safety of traffic operations only indirectly—through reduction of some

TABLE 13
ATCS EVALUATION STUDIES

Type of Evaluation Study	Percent of Agencies
Field evaluation	89
Evaluation in microsimulation	11
Before-and-after study	65
On and off study	35

Note: The first and the second evaluation types are mutually exclusive, as well as the third and the fourth; hence, total percentage equals 200.

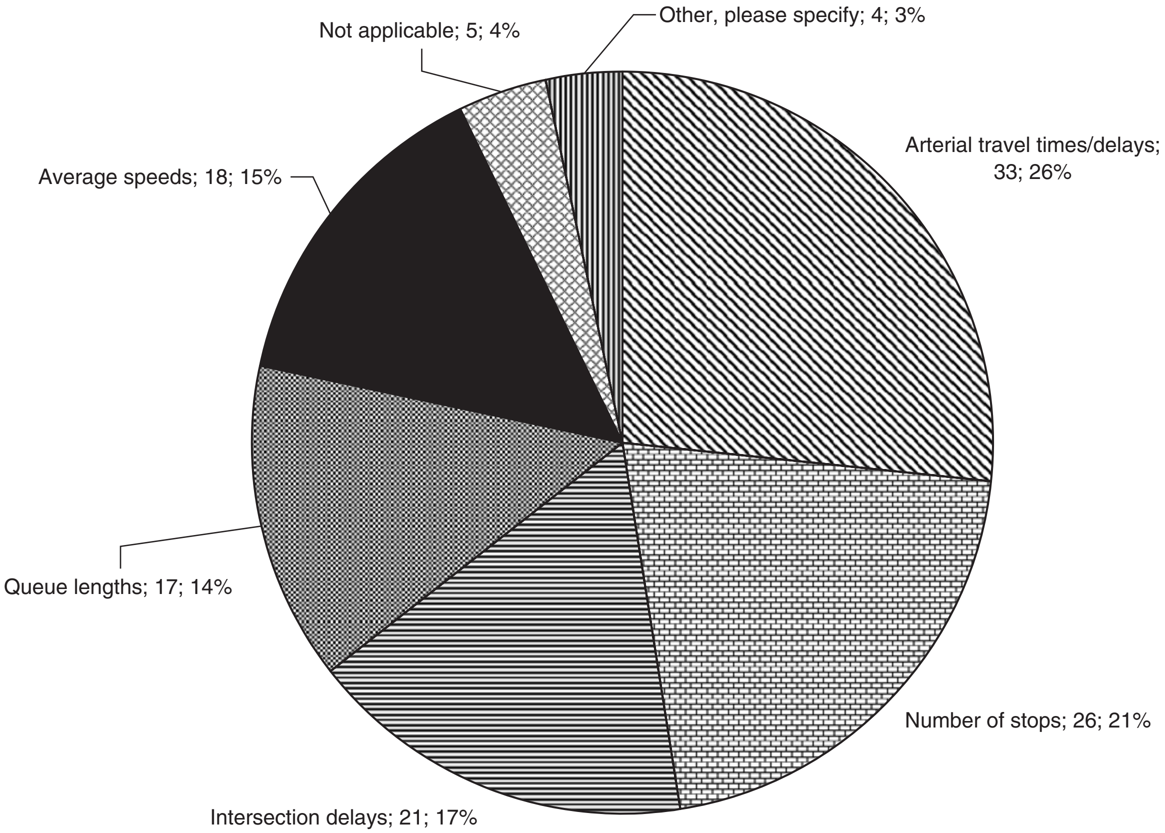


FIGURE 14 Most common performance measures to evaluate an ATCS.

efficiency-related performance measures, which highly correlate with some safety metrics (e.g., a reduction in the number of stops reduces the chance of rear-end collisions).

The benefits of ATCS deployments are reported in numerous studies published during the last 30 years, since the first practical applications of the systems. There have been studies that reported 40% (and higher) improvement in certain performance measures after the ATCS has been deployed and the others that did not find any improvements or found that the operations worsened after ATCS installations. Although ATCSs have been shown to provide benefits in most cases, it is difficult to provide a detailed overview of the benefits for any of the systems, as each technology works differently, and each implementation is unique and customized to that particular deployment site. Figure 15 shows a summary of the results from evaluation studies conducted at deployment sites covered by the survey. Most of the ATCS users reported (based on their evaluation studies) that their ATCSs perform much better than their previous conventional traffic signal systems [e.g., TOD plans executed through fixed-time or actuated (coordinated or isolated) traffic control]. Thirty-two percent of the respondents found that ATCSs are better, whereas 14% reported that no benefits of the ATCS were observed. Finally, only 5% of the ATCSs have performed worse than the previous type of traffic control system, whereas 11% of respondents did not report any findings.

When these generalized findings are disaggregated into various performance measures it is found that 60% of ATCS users observe a reduction in travel times/delays when such a system is deployed. Similarly, deployments of ATCSs reduce the number of stops, intersection delays, and queue lengths in 37%, 37%, and 23% of the cases, respectively. Increases in average speeds have been observed by 35% of the ATCS users.

The benefit of an ATCS in oversaturated traffic conditions is one of the most controversial aspects of the system's performances. Many ATCS users state that the systems do not help significantly in oversaturated traffic conditions, although others have stated the opposite. The survey indicates that only a very small percentage of the interviewed agencies (3%) recognize that their ATCSs prevent or eliminate oversaturation. The majority of the interviewed agencies reported that their ATCSs reduce or eliminate the extent of the periods of oversaturation. Approximately 33% of ATCS users have found the systems to be counterproductive in oversaturated traffic conditions. Figure 16 shows two separate categories (Question 11 under points c. and e.) that were combined to obtain this percentage (comments under "Other, please describe" mostly report that ATCSs are not useful for oversaturation).

Considering the responses on ATCS benefits in oversaturation, and that oversaturation mostly occurs in peak periods,

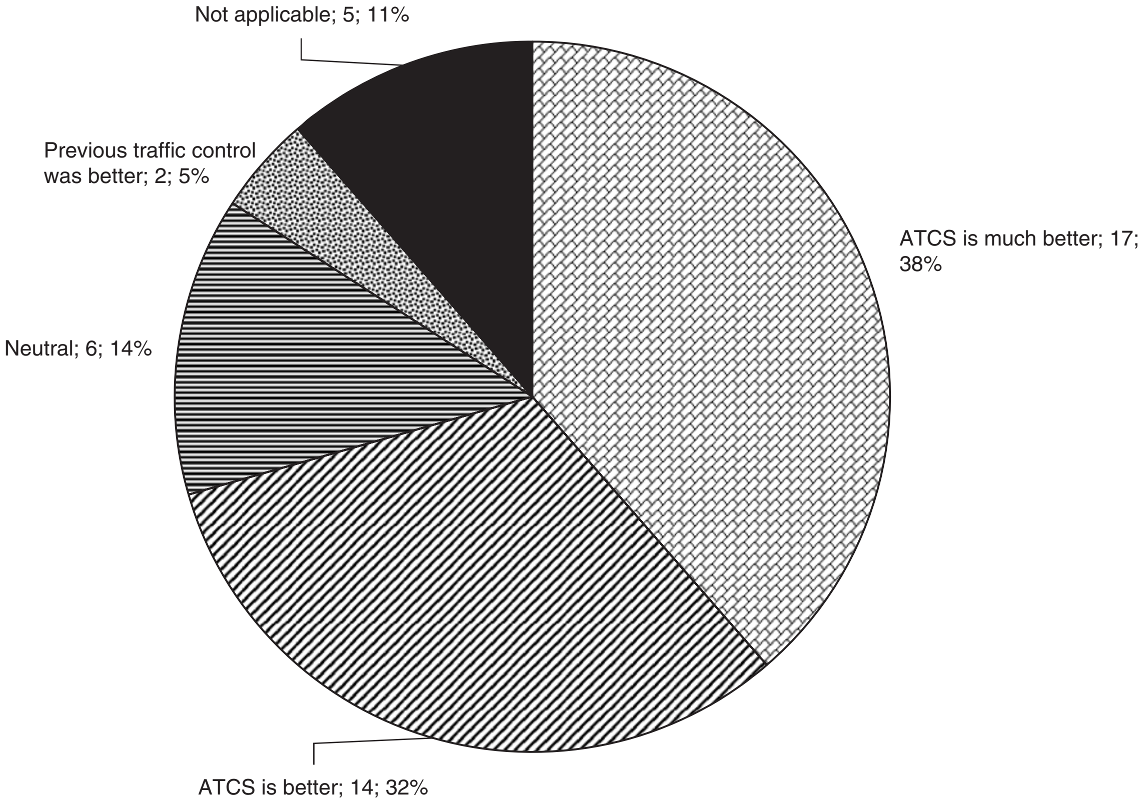


FIGURE 15 Comparison of performances: ATCS vs. other traffic control.

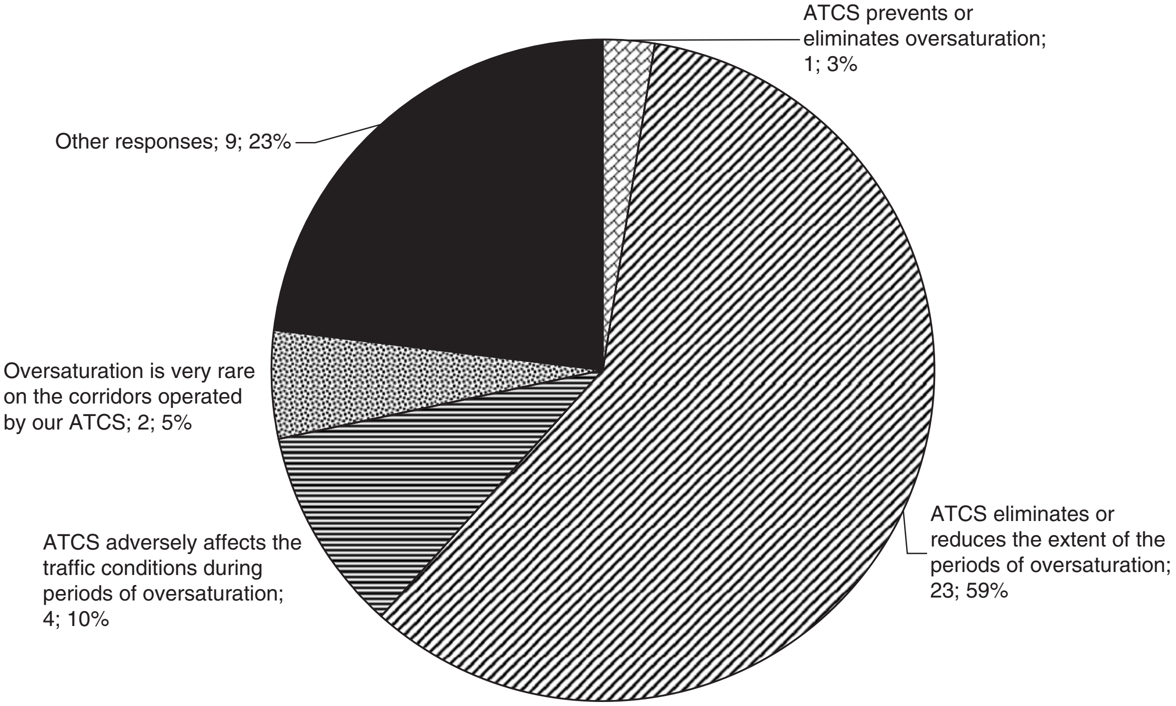


FIGURE 16 ATCS performance in oversaturated traffic conditions.

one would expect to see that an ATCS performance in peak periods is not so beneficial. However, the survey reported that 37% of the agencies found ATCSs to be the most effective during peak periods. Twenty-three percent of the agencies found the highest ATCS benefits during the off-peak periods, whereas 23% of the ATCS users found ATCSs to be the most beneficial at the shoulders of peak traffic periods. Another 19% selected combinations of the aforementioned options. These results are slightly counterintuitive when one considers findings about weak benefits of ATCSs in oversaturation. Most likely, oversaturated conditions experienced by the interviewed agencies do not extend over the entire length of the peak periods. Therefore, because oversaturated conditions are shorter than peak periods, ATCSs are considered to be beneficial during those parts of peak periods when there is no oversaturation.

ATCS operations can degrade over time owing to changes in operational traffic conditions and the inability of some of the ATCS parameters to self-adjust to those changes. Some of the ATCS' user manuals document parameters that are subject to the "ageing" process. It appears that most of the ATCSs can cope well with degradation in their performance. Most of the ATCS users (79%) find that their ATCSs have achieved a sustained level of performance since the initial installations; another 21% believe the opposite. One could note that only a few of the ATCS users have done multiple evaluation studies during the course of their ATCS deployment.

Multiple evaluation studies can be used to objectively document that the level of ATCS performance has been sustained. The following list shows some examples of ATCS' users' responses on specific benefits and costs observed in operations of their ATCS deployments.

- Advantages
  - Fuel consumption benefits
  - City council sees the increase in efficiency
  - Thirty-three intersections resulted in more than $1 million in fuel reduction
  - Just the normal obvious benefits with adaptive control
  - Reduction in air pollution
  - $583,996/$542,511 one-year ratio of benefits/costs
  - Engineer less exposed in field
  - Decreased time to develop signal timings
  - Public transport priority and emergency vehicle priority
  - Lower cycle lengths—better pedestrian response
  - Accommodates roadwork and special events.
- Negatives
  - Cost of software maintenance too high for the city
  - Save in costs of conducting traffic counts—system does it for you
  - Extremely expensive to maintain
  - Requires substantial manpower to maintain system
  - Additional overhead for maintenance/licensing
  - Costs of communications and training
  - Extensive experience necessary to get most benefits.

PUBLIC PERCEPTION

Installation of an ATCS does not readily provide observable benefits to the traveling public. If the previous conventional traffic signal control was maintained properly it may be difficult for an ATCS to achieve benefits higher than 10% to 15% for any of the performance measures. Indeed, a 10% to 15% reduction in delays and stops is something that an everyday traveler may not notice easily. Despite this some agencies decide to conduct a public education campaign in which they attempt to familiarize the traveling population with the new system and its working principles.

One of the primary reasons for conducting public education campaigns is that agencies implementing ATCSs would like to justify, to the travelers, reasons for potential changes in traffic signal operations and thus reduce the potential number of complaint calls. Travelers who are convinced that, overall, the new system provides more benefits than the old one may not complain as much about certain operations that may become worse through ATCS deployment. However, in spite of the good intentions, the decision to conduct an education campaign may bring more problems than benefits. Actually, at times the number of complaint calls increases after installation of a new ATCS not because the performance of the new system is worse, but because travelers subjectively believe that things have worsened with the installation of the new system. For this or similar reasons many ATCS agencies do not conduct public education campaigns. Results from our survey show that approximately 58% of ATCS users never launched an education campaign about deployment of their system. Of those agencies that conducted public education campaigns there are none that reported that the campaign was effective. Sixteen percent of the interviewed agencies found that their campaigns were somewhat effective and another 25% reported that the campaign was either neutral (23%) or slightly ineffective. Interestingly, no agency reported that the campaign was very ineffective. One might also note that deployment of an ATCS represents an action (by an ATCS agency) that is done to ease traffic congestion and improve arterial traffic operations. As such, this action has some political weight, and it is important that its promotional benefits not be underestimated.

Surveying travelers to investigate the impact of newly installed ATCSs on traffic performance is not a common way to evaluate the quality of an ATCS. However, some agencies perform such a survey expecting to catch potential ATCS benefits that might be missed by common traffic engineering studies (e.g., travel time, stop, and delay studies). Of all interviewed ATCS users only 33% conducted any public perception survey to catch benefits of ATCS deployment. Results of those surveys were reported in Table 14.

TABLE 14
PUBLIC PERCEPTION SURVEY ON ATCS DEPLOYMENTS

Results from Public Perception Survey	Percent of Agencies
Clearly supportive	21
Somewhat supportive	36
Neutral	36
Unsupportive	7

SUMMARY

This chapter identified the major costs and benefits associated with ATCS deployments. Licensing costs to install proprietary software are only 10% to 15% of the overall installation costs and they do not appear to represent a significant cost to customers. The survey results showed that ATCS installation costs per intersection (approximately $65,000) are higher than reported in the previous literature (approximately $40,000). Interestingly, ATCSs require less money than conventional traffic signals for their physical maintenance, when their shares in overall budget and overall operations are compared. This finding contradicts the common belief in the traffic signal community, where ATCSs are known for the costly maintenance of their detectors and communication systems. Most agencies prefer to hire outside consultants for ATCS evaluations, who mainly perform field evaluations through a set of before-and-after studies. Other alternative methods of performing evaluations are much less frequently represented.

The chapter also provided a list of the most common performance measures collected during the ATCS evaluations. The majority of the users' evaluations (71%) reported that ATCSs outperformed conventional traffic signal systems. However, the benefits of ATCS deployments are not observable in oversaturated traffic conditions. Although ATCS users find that their systems delay the start of oversaturation and reduce its duration, ATCSs are not recognized as a cure for oversaturated traffic conditions. Most of the users do not perceive that the performance of their ATCSs degrade over time—a finding that is quite remarkable considering some of the user comments. Public education campaigns about ATCS deployments are not very common or effective, as indicated by most of the ATCS users. Also, not many of the ATCS agencies conduct public perception surveys. Those agencies that do reported that results from such surveys are supportive approximately 60% of the time. The next chapter focuses on lessons learned communicated through user perspectives on several questions from the survey.

CHAPTER SEVEN

LESSONS LEARNED

INTRODUCTION

Each deployment can be different and challenging both to the vendor who installs the ATCS and the agency that operates and maintains the system. Each deployment process is also a learning experience from which agencies can determine what could have been done differently. This chapter identifies major lessons learned through a series of questions answered by interviewed ATCS users. First, ATCS users' positive and negative surprises from ATCS deployments were noted and then the agencies provided their hindsight perspectives. Subsequent sections also present factors that caused several ATCS shutdowns, problems that prevent further ATCS expansions, and the potential for future ATCS deployments.

USER PERSPECTIVES

Positive and Negative Surprises from Adaptive Traffic Control Systems Deployments

The deployment of an ATCS is a challenging process for both ATCS users and the vendors and consultants who perform system installation and integration. No two ATCS deployments are the same. Idiosyncratic characteristics of deployment site, traffic conditions, an agency's legacy hardware and software, and the institutional and cultural characteristics of the agency, make each ATCS deployment unique. For this reason each new ATCS deployment represents a new learning experience both for the agency and the vendor. Although there is significant literature on ATCSs, people who have not worked with an ATCS before tend to get a skewed picture about its abilities. This picture is sometimes intentionally skewed by ATCS vendors who are trying to sell intellectual properties and consulting services for an ATCS to as many customers as possible. From that perspective, it is interesting to discover what operational surprises are noticed by agencies during their deployments. The following list shows examples of positive and negative surprises.

- Positive
  - How well it responded to changing traffic conditions
  - Short system response time to fluctuating demands
  - Effectiveness of the system
  - Does adapt to daily commuter traffic
  - How well it worked; traffic data stored
  - Moving special events traffic efficiently
  - Better than expected results in before-and-after study
  - It worked with NEMA controllers and cabinets
  - System is very flexible
  - Side street venue dumps were dramatically improved
  - Centralized control, performance measures
  - Successful possible signal coordinating
  - Spillback on Interstate reduced
  - Good early learning opportunities for ATCS
  - Appeared to handle delays about as well as promised.
- Negative
  - Black box—difficult to explain signal operation
  - Video detection system a high maintenance effort
  - Had hardware issue with communications, but it was resolved
  - Lots of effort required to keep optimal performance
  - Steep learning curve
  - System difficulty and lack of support
  - Hardware was discontinued by manufacturer
  - Much more sophisticated and complicated than told
  - Initial set-up costs and time taken
  - Amount of time needed for deployment
  - Time and effort to debug central and field equipment
  - Importance of communications
  - Some phases not being served in early deployment
  - Design consultant made mistakes
  - There was a recurring issue with phase skipping.

People were mostly pleasantly surprised by ATCS's abilities to provide what was observed as "efficient operations" and to adjust to within-day and day-to-day traffic fluctuations. The second important positive surprise related to a systems ability to store traffic data that previously required much more difficult data collection efforts. Negative surprises were mostly related to difficulties in learning how to operate the system and hardware issues (mostly communications). There were also some complaints about operational features of the systems (e.g., phases being skipped), which reflect a lack of hands-on expertise within the agency, availability of local technical support, or problems with hardware more than deficiencies in operational philosophies of their ATCSs.

There is a notion that some ATCS users jumped into installing an ATCS to replace an outdated fixed-time or isolated traffic signal system. In such cases, the agencies wondered if the same operational benefits, which are achieved with the ATCS, could be achieved with conventional actuated-coordinated traffic control.

Hindsight Perspectives

To summarize what agencies have learned through their ATCS deployment processes we asked them to answer what they would, in hindsight, have done differently during the implementation of their ATCSs. Most of the responses indicated that greater emphasis might be given to local support, either through acquiring more in-house knowledge or by ascertaining that technical support for their ATCS is available locally. Better planning and preparation of the necessary infrastructure (communications and detection) are the next important issues that most agencies would have done differently. Finally, some agencies recognized that they would need more information on the costs and benefits associated with installation of ATCS.

The following is a list of the actions, summarized in four major categories, which the interviewed ATCS users would have done, in hindsight, for their ATCS implementations.

- Secure good local support from the vendor by
  - Asking for dedicated support field staff; insisting on local vendor support
  - Spending more time with the vendor's engineer(s)
  - Keeping a more watchful eye on the contractor installing the system; design consultant had no expertise in ATCS. Vendor, at first, did not supply the people with the most expertise—so the design consultant made mistakes that had to be changed post-installation
  - Waiting for vendor-supported product rather then deployed test application.
- Improve the planning process to avoid in-house operational and institutional issues by
  - Starting with a larger region
  - Allocating more time for debugging
  - Getting buy-in from operational staff and not just the steering committee and project management
  - Involving local staff at a much earlier stage and achieving full independence and expertise earlier as a result
  - Doing it all in-house from the start
  - Appointing the necessary expertise to manage the network.
- Prepare infrastructure (e.g., detection and communications) for an ATCS deployment by
  - Replacing all existing equipment—not retrofitting
  - Using conventional loop detection or established non-intrusive detection rather than the first release of a new model of video detection
  - Testing (thoroughly) local control firmware and ease of use for technicians
  - Reviewing and planning for better communications; adding CCTVs for monitoring
  - Waiting for more current algorithms to be developed before deployment; putting more thought into detector placement
  - Using inductive loop detection exclusively; microwave detection was used for about half of the links to reduce installation costs—they turned out to be extremely unreliable
  - Using 170 controllers, installing new communications (fiber or twist pair) everywhere (tried to use existing old twisted pair), starting smaller and then expand out.
- Conduct a detailed pre-installation evaluation to estimate the operational benefits of an ATCS before deciding to implement an ATCS by
  - Gathering more before-and-after data
  - Not deploying an ATCS at areas with normal traffic conditions
  - Running the operations with traffic signals under actuated coordination before deploying an ATCS.

Factors That Caused System Shutdowns

Lessons learned might also include instances where ATCSs were turned off. Although the few agencies that turned off their ATCSs did not provide specific details to justify their decisions, the following is a list of major factors that influenced those decisions:

- Improper detection layout and other operational problems;
- Multiple simultaneous events: budget reductions, staff reassignments, construction projects (resulting in significant removal of system detection);
- Operational problems; agency did not shut down the entire system, but it turned most of the ATCS signals to actuated-coordinated operations;
- System incompatibility with ramp-metering where integration of arterial and ramp operations was required; and
- No operational benefits achieved; problems with hardware and software.

Problems Preventing Expansion of Adaptive Traffic Control System

The results from the survey indicated that the high cost of ATCS deployments is the most prohibitive factor to expanding current ATCSs (50% of the cases). The second factor, by importance, is the lack of traffic signal operations staff—a problem that can also be attributed to inadequate funding. Finally, some agencies reported that the operational inefficiency of their ATCSs is the major reasons they have not expanded their systems. The following is a list of the major reasons that interviewed ATCS agencies were prevented from expanding their systems spatially (to neighboring intersections) and temporally (to be used 24 hours a day/7 days a week):

- Insufficient staff and funding to operate and maintain;
- Poor communications between vendor and client;
- Not cost-effective if volume fluctuations are insignificant, or where cycle lengths and splits are too constrained to meet operational objectives;

- Costs of licensing fees and the highly sophisticated expertise needed to set up and fine-tune the system. In addition, it requires lots of vehicle detection that is well-maintained and working properly;
- Difficult to program and data intensive;
- High cost of supplying communications or low-priority sites; and
- Only use it at times of high traffic flows, as standard vehicle actuation is more reactive at quieter times when linking becomes less important.

Future Adaptive Traffic Control System Deployments

Approximately 73% of the ATCS users interviewed would install the same system again. The remaining 27% of the ATCS users, who would not install the same ATCS, indicated various reasons for such a decision. The single greatest problem is the high cost of operating and maintaining an ATCS. Other problems, as shown in Figure 17, included high installation costs and a lack of expertise within an agency. Also, ATCS users found, with an approximately equal level of importance, that they did not achieve the expected benefits from their systems and that technical support is weak. Only 5% of the interviewed agencies would not install the same ATCS because they are convinced that other ATCSs work better. Interestingly, when results from Figure 4 and Figure 17 are compared, it can be noted that 79% are satisfied with their systems, but only 73% would install the same systems again. This difference in the results can be explained with combinations of the factors against another ATCS deployment, which are shown in Figure 17.

To determine whether there is any relationship between the size of an ATCS and user satisfaction of the agency that runs the ATCS, responses on the question from Figure 17 were divided into two categories. One category represented large ATCS deployments with 50 or more intersections under an ATCS and the other category included all other ATCS deployments. The findings showed that approximately 90% of the users with large ATCS deployments would install their systems again versus only 47% of users of small ATCSs. The findings imply that users with more intersections under an ATCS have a better experience with their ATCSs. The better experience is most likely the result of more resources that are available to these agencies to operate and maintain ATCSs, more staff to develop and maintain in-house expertise, and more attention being given by ATCS vendors.

SUMMARY

This chapter identified lessons learned by ATCS users from various perspectives such as deployment surprises, hindsight opinions, factors that influenced ATCS turn-offs, reasons preventing ATCS expansions, and potential for new ATCS deployments. ATCS agencies were mostly pleasantly surprised by the system's abilities to provide what was

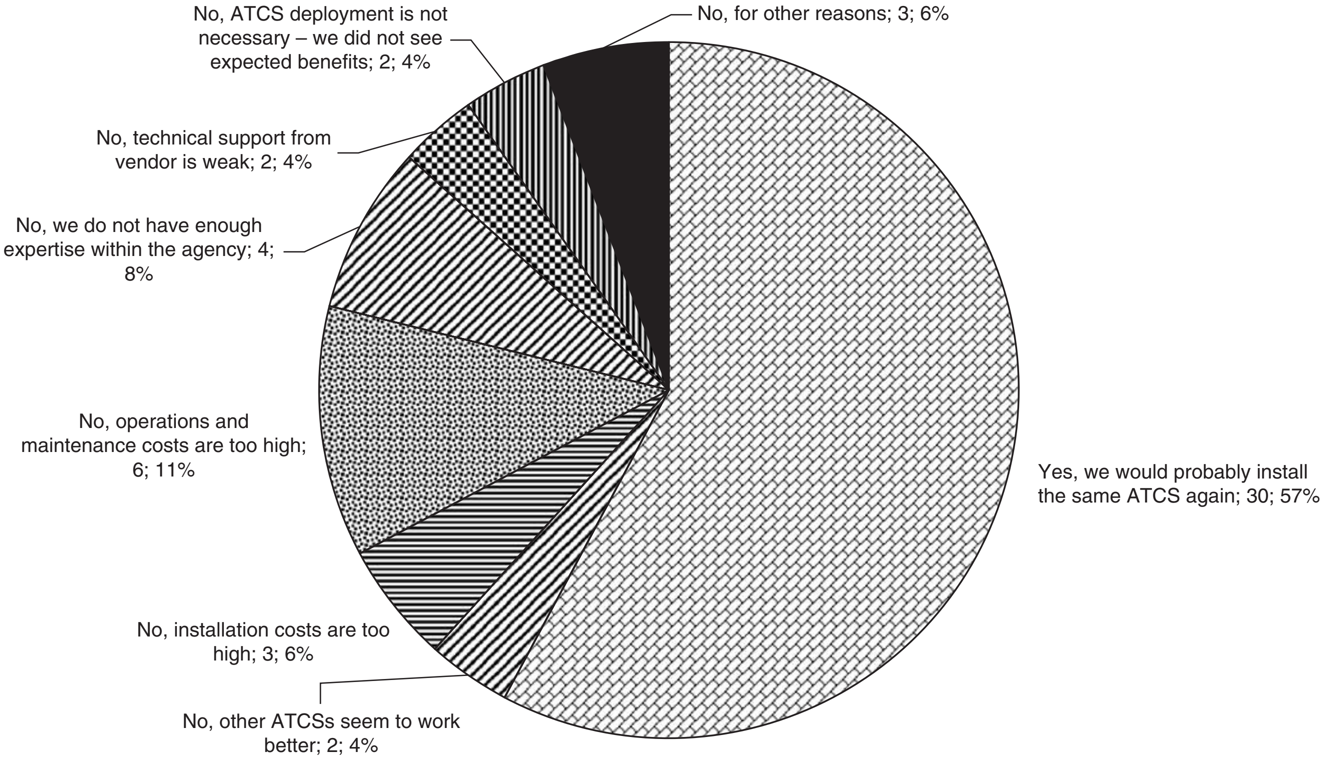


FIGURE 17 Deploying an ATCS again. Would you install the same ATCS in another location?

observed as efficient operations and to adjust to within-day and day-to-day traffic fluctuations. Negatives were mostly related to difficulties in learning how to operate the system and hardware issues (mostly communications). Lessons learned can be summarized in four categories: (1) better local support from the vendors; (2) better planning for in-house support; (3) a good preparation of the infrastructure (detection and communications); and (4) detailed pre-installation evaluation to estimate operational benefits. When an ATCS was turned off it was done for a variety of reasons; with low operational benefits being one of the major reasons. A major reason preventing ATCSs from further expansions are the high costs related to operating and maintaining an ATCS (e.g., employing and training the staff). Overall, most ATCS users (73%) would install the same system again. This number increases when larger ATCS deployments are considered. Smaller systems tend to have more problems in securing funding and therefore their overall experience with an ATCS is not as positive. Major drawbacks for those agencies that would not install the ATCSs again are the high costs of operating and maintaining an ATCS (where the emphasis is given to operations and engineering and not physical maintenance), weak (local) technical support, and that the benefits of running an ATCS are not always clearly expressed. The next chapter provides the conclusions drawn from the study.

CHAPTER EIGHT

CONCLUSIONS

The study findings were based on a literature review and two electronic surveys: a shorter e-mail survey for vendors or developers of 10 major adaptive traffic control systems (ATCSs) and a main website-based questionnaire for agencies that deploy ATCSs. The main survey was originally distributed to 42 agencies that run ATCSs in North America (United States and Canada) and several dozen locations around the world. Numerous follow-up requests were made, by e-mail and phone, to remind agencies that had not yet responded, asking them to participate in the survey. Responses were obtained from 34 of 42 agencies in North America, an 81% response rate. Also, 11 responses were received from agencies in other countries. Of the North American agencies, 42% were municipal entities, 20% were counties, 13% were state agencies, and 25% were other.

The survey indicated that ATCS agencies deploy their ATCSs in operational environments where the systems are known to provide the best performance. Most of those interviewed have 10% to 30% of their traffic signals under the ATCS. Handling daily and weekly fluctuations in traffic flows is the highest ranked reason for ATCS deployments. When procuring an ATCS, agencies frequently consider multiple systems. On average, an ATCS installation takes approximately 18 months, from the time when funding is made available to the time an ATCS becomes fully operational. Most of the ATCSs that have been deployed during the last 20 years are still in operation. If an ATCS is shut down it is usually the result of several negative factors. Agencies frequently expand their ATCSs and, in general, most are satisfied with their operations.

Review of the most widely used ATCSs showed that various systems use similar strategies to cope with fluctuations in traffic demand and distribution. However, each tool is unique and without direct comparison it is difficult to compare the algorithms and adaptive logic of the various tools. Field implementations of various tools are even more unique than their logics, which makes direct field evaluations expensive and therefore impractical. For this reason, among others, very few studies in the literature provide evidence that the operational concepts of one particular ATCS are better than those of another.

There is a considerable need for expertise to ensure a successful ATCS implementation. Although many agencies implement ATCSs to reduce labor-intensive maintenance of signal timing plans, survey respondents indicated that ATCSs are only tools for traffic management and they need to be supervised and controlled by skilled engineering staff. Proper training and acquisition and retention of expertise within an agency were reported as the most important factors for alleviating institutional barriers for ATCS deployment. ATCS operations are often not perceived as being difficult; however, it appears that ATCS users are not often given the opportunity to learn how to fully operate their systems. One of the reported operational problems indicated a lack of the basic knowledge for operating an ATCS. A majority of the ATCS users rely on in-house expertise, which is more an indication of not having adequate resources to hire outside support than that ATCS users are fully trained to control and operate their systems. In general, ATCS users would like to acquire additional expertise; however, the agencies do not have enough financial resources to acquire comprehensive training, and most of the agencies are short staffed. ATCSs are considered more operationally demanding than conventional traffic signal systems; however, agencies are not able to support these systems in the same way they support conventional traffic signal systems. Unlike conventional systems that are maintenance-intensive, ATCSs require more emphasis on the expertise necessary to operate their sophisticated operations. This switch in the type of labor (from maintenance to operations), which is needed to support proper ATCS operations, is often not recognized by an agency until the ATCS is already deployed. This inability to recognize the need for additional operational expertise in a timely manner can adversely affect the ATCS performance. If the agency is disappointed with the performance, it will be reluctant to expand on the existing system or to procure new ATCSs.

Detection requirements for an ATCS are slightly higher than those for conventional traffic-actuated control systems. Most of the ATCS users are satisfied with the way their system handles minor detector malfunctions. Some ATCS users have difficulties with the handling of ATCS-specific hardware, although this is primarily an issue that could be resolved with better training of the technical staff. ATCSs mainly operate on Windows-based platforms and are sometimes integrated with one of the available Advanced Traffic Management Systems (ATMSs). Integration with an ATMS, which is not common, has become more frequent with recent ATCS implementations. As perceived by most of the users, ATCS software is one of the components that need improvement. Interestingly, ATCS users do not find that ATCS communications cause many more problems than the communications of conventional traffic control systems. However, communications play a much more important role in ATCS deployments and for this reason need to be regularly maintained, which represents one of the major operational costs for ATCS users.

The survey results showed that ATCS installation costs per intersection are approximately $65,000 and are higher than previously reported. Interestingly, results showed that ATCSs require less funding for physical maintenance than conventional traffic signals. This finding contradicts common belief present in the traffic signal community that maintenance of ATCS detectors and communications is costly.

When ATCSs are evaluated most agencies prefer to hire outside consultants, which primarily perform field evaluations through a set of before-and-after studies. A majority of the user evaluations reported that ATCSs outperformed conventional traffic signal systems.

The benefits of ATCS deployments are not easily observable in oversaturated traffic conditions. Although ATCS users find that their systems may delay the start of oversaturation and reduce its duration, they are not recognized as a cure-all for such traffic conditions. However, modifications of an ATCS to reduce oversaturation is often beyond the competence level of ATCS users; therefore, there is little data available to draw conclusions about ATCSs' performances in oversaturation.

Most users do not perceive that the performance of their ATCS degrades over time. Public education campaigns about ATCS deployments are not very common and effective, as indicated by most ATCS users. Also, not many ATCS agencies conduct public perception surveys. Those agencies that do reported that results from such surveys are supportive approximately 50% of the time.

ATCS agencies were mostly generally satisfied by their systems' ability to provide what was observed as "efficient operations" and to adjust to within-day and day-to-day traffic fluctuations. Negatives were mostly related to difficulties in learning how to operate the system and the hardware (primarily communications). Lessons learned can be summarized in four categories, which represent pre-deployment actions necessary for successful ATCS implementation: better local support from vendors; better planning for in-house operational and institutional support; good preparation of the infrastructure (detection and communications); and detailed pre-installation evaluation to estimate operational benefits. Major reasons that prevent ATCSs from further expansion include the high costs related to operating and maintaining the system (e.g., employing and training the staff).

Overall, most of the surveyed ATCS users (73%) would install the same system again. Users with more signals under an ATCS have more satisfactory experiences with ATCS operations. More signals under an ATCS attract more attention within the agency, and therefore more resources to operate and maintain the ATCS, more staff to develop and maintain in-house expertise, and finally more attention from ATCS vendors. Smaller systems are inclined to have more problems securing funding and hence their overall experience with ATCSs is not as positive.

Although specific recommendations were not requested in the survey, survey recipients suggested the following research to improve knowledge of ATCS implementations in the United States and other countries.

- Explore establishing a coalition for Adaptive Traffic Control, which could serve as a framework for exchanging experiences and lessons learned about ATCS deployments. Agencies with smaller budgets for ATCSs may particularly benefit from such a coalition. One of the first priorities could be to investigate factors that represent barriers for new agencies to deploy an ATCS.
- Research into funding operations by an ATCS including the Transportation Pooled Fund Program and other similar programs that could provide resources to conduct further studies on these systems to address the most important and urgent issues.
- More study is needed to estimate the true benefit–cost ratios of ATCS deployments. There is a need for comprehensive evaluation studies that would show all of the costs and benefits of an ATCS deployment (including investigation of the long-term operational savings resulting from long-term changes in traffic demand).
- ATCS agencies could be encouraged to document and analyze implementation issues (i.e., staff retention) to identify the costs and benefits associated with the use of an ATCS when compared with the deployment of conventional traffic control systems. Potentially, these documenting efforts could be a requirement imposed, and financially supported, by federal authorities. Demonstrating benefits can promote more extensive and more appropriate use of ATCSs.
- More research is needed to investigate various funding sources used to deploy ATCSs. Research on how much funding is necessary to support various components of ATCS installations [e.g., cost of hardware (electronics), software, and labor (installation, maintenance, and operations)] is also needed. It could be also investigated how agencies make decisions to deploy ATCSs and whether decisions are made in coordination with operational staff.

REFERENCES

Boillot, F., J.M. Blosseville, J.B. Lesort, V. Motyka, M. Papageorgiou, and S. Sellam, "Optimal Signal Control of Urban Traffic Networks," *Proceedings of the IEE Conference on Road Traffic Monitoring,* IEE Conference Publication No. 355, 1992, pp. 75–79.

Crenshaw, P., "FHWA Adaptive Control Survey," presented at the TRB A3A18 (Committee on Traffic Signal Systems) Meeting, 2000 Midyear Meeting Minutes, Seattle, Wash., July 9–10, 2000.

Donati, F., V. Mauro, G., Roncolini, and M. Vallauri, "A Hierarchical Decentralised Traffic Light Control System," *Proceedings from IFAC 9th World Congress,* Vol. II, 11G/A-1, 1984.

Fehon, K., "North American Development of Adaptive Traffic Signal Systems," *Proceedings of the ITE 2005 Annual Meeting and Exhibit Compendium of Technical Papers,* Melbourne, Australia, Aug. 5–7, 2005, 17 pp.

Friedrich, B., T. Sachse, M. Hoops, W. Jendryschik, and G. Reichert, "Balance and Varia Methods for Traffic Adaptive Control," *Proceedings of the Second World Congress on the ITS,* Yokohama, Japan, 1995, pp. 2356–2361.

Gartner, N.H., *Demand-Responsive Decentralised Urban Traffic Control,* Report DOT/RSPA/DPB-50/81/24, U.S. Department of Transportation, Washington, D.C., 1982.

Gartner, N.H., F.J. Pooran, and C.M. Andrews, "Implementation and Field Testing of the OPAC Adaptive Control Strategy in RT-TRACS," *Journal of the Transportation Research Board,* Washington, D.C., 2002, pp. 148–156.

Gordon, R.L. and W. Tighe, *Traffic Control Systems Handbook,* Report FHWA-HOP-06-006, Office of Transportation Management, Federal Highway Administration, Washington, D.C., Oct. 2005, 367 pp.

Head, K.L., P.B. Mirchandani, and D. Shepherd, "A Hierarchical Framework for Real-Time Traffic Control," *Transportation Research Record 1360,* Transportation Research Board, National Research Council, Washington, D.C., 1992, pp. 82–88.

Henry, J.J., J.L. Farges, and J. Tufal, "The PRODYN Real Time Traffic Algorithm," *Proceedings of the IFAC Symposium,* Baden-Baden, Germany, 1983.

Hicks, B. and M. Carter, "What Have We Learned About ITS Arterial Management?" In *What Have We Learned About Intelligent Transportation Systems?* Federal Highway Administration, Washington, D.C., Dec. 2000, pp. 45–63.

Holroyd, J. and J.A. Hillier, "The Glasgow Experiment: PLIDENT and After," *RRL Report 384,* Transport and Road Research Laboratory, Crowthorne, Berkshire, United Kingdom, 1971.

Hunt, P.B., D.I. Robertson, R.D. Bretherton, and R.I. Winton, "SCOOT—A Traffic Responsive Method of Coordinating Signals," *Report TRRL 1014,* Transport and Road Research Laboratory, Crowthorne, Berkshire, England, 1981, 44 pp.

Jayakrishan, R., S.P. Mattingly, and M.G. McNally, *Performance Study of SCOOT Traffic Control System with Non-Ideal Detectorization: Field Operational Test in the City of Anaheim,* Report UCI-ITS-WP-00-27, Institute of Transportation Studies, University of California, Irvine, Dec. 2000.

Kruse, G., "MOTION—Signal Control for Urban Road Networks," presented at the TRB Midyear Traffic Signal Committee Meeting, Adaptive Traffic Signal Control Workshop, Pacific Grove, Calif., July 12–14, 1998.

Lowrie, P.R., "The Sydney Co-ordinated Adaptive Traffic System—Principles, Methodology, Algorithms," *Proceedings of the International Conference on Road Traffic Signaling,* Institution of Electrical Engineers, London, U.K., Vol. 207, 1982, pp. 67–70.

Malek, S., R. Denney, and J.A. Halkias, "Traffic Signal Control Systems," In *Advanced Transportation Management Technologies Participant Notebook,* Report FHWA-SA-97-060, Federal Highway Administration, Washington, D.C., 1997, pp. 3.1–3.15.

Mauro, V. and C. DiTaranto, "UTOPIA," Control, Computers, Communications in Transportation: Selected Papers from the IFAC Symposium, 1990, pp. 245–252.

Mirchandani, P. and L. Head, "A Real-Time Traffic Signal Control System: Architecture, Algorithms, and Analysis," *Transportation Research Part C: Emerging Technologies,* Vol. 9, No. 6, Dec. 2001, pp. 415–432.

Mueck, J., "Recent Developments in Adaptive Control Systems in Germany," *Proceedings of the 12th World Congress on ITS,* San Francisco, Calif., Nov. 6–10, 2005, 11 pp.

Pesti, G., P.S. Byrd, M. Kruse, and P.T. McCoy, *Evaluation of the SPOT Adaptive Traffic Control System,* FHWA Technology Project No. 97068, Federal Highway Administration, Nebraska Department of Roads, Lincoln, May 1999, 35 pp.

Shelby, S.G., D.M. Bullock, D. Gettman, R.S. Ghaman, Z.A. Sabra, and N. Soyke, "Overview and Performance Evaluation of ACS Lite—A Low Cost Adaptive Signal Control System," No. 08-0334, 87th Annual Meeting of the Transportation Research Board, Washington, D.C., Jan. 13–17, 2008, 17 pp.

Taale, H., W.C.M. Fransen, and J. Dibbits, "The Second Assessment of the SCOOT System in Nijmegen," In *Proceedings of the IEE Road Transportation Information and Control Conference,* Publication No. 454, London, United Kingdom, Apr. 21–23, 1998.

Xin, W., W.R. McShane, S. Muthuswamy, and J. Chang, "An Integrated Real-Time Decision Support System for Adaptive Signal Control," In *Proceedings of the 15th World Congress on Intelligent Transport Systems,* New York, N.Y., Nov. 11–16, 2008.

ACRONYMS

ACS	Adaptive Control System
ATC	Advanced traffic controller
ATCS	Adaptive Traffic Control System
ATMS	Advanced Traffic Management System
CCTV	Closed-circuit television
DOT	Department of Transportation
ITS	Intelligent Transportation System
MIST	Management Information System for Transportation
NEMA	National Electrical Manufacturers Association
OPAC	Optimization Policies for Adaptive Control
PRODYN	Programming Dynamic
RHODES	Real-Time Hierarchical Optimized Distributed and Effective System
RT-TRACS	Real-Time Traffic-Adaptive Signal Control System
SCATS	Sidney Coordinated Adaptive Traffic System
SCOOT	Split Cycle Offset Optimization Technique
SPOT	System for Priority and Optimization of Traffic
TOD	Time-Of-Day
TRANSYT	Traffic Network Study Tool
UTOPIA	Urban Traffic Optimization by Integrated Automation
VMS	Virtual Memory System

APPENDIX A

Vendors' Descriptions of Major Adaptive Traffic Control Systems

References cited in this appendix can be found in Appendix C.

ACS LITE

FHWA initiated development of *Adaptive Control Software Lite* (ACS Lite), prescribing a lower cost and more easily managed system, to surmount the major deployment impediments and bring this rarely used state-of-the art technology to the mainstream state of practice (Curtis et al. 2009). ACS Lite offers significant cost savings relative to earlier FHWA-sponsored adaptive systems by better leveraging existing infrastructure; evaluations based on both field trials and simulation studies have shown significant benefits, such as delay reductions of up to 35% (Shelby et al. 2008). The following discussion provides a more detailed description of the ACS Lite system architecture, adaptive logic, and evaluation results to date.

Project History

The research and development of ACS Lite has been done by Siemens, with collaboration from other partners including major signal controller manufacturers Eagle (now Siemens), Econolite, McCain, and Peek, who accepted an invitation from FHWA to participate in the project (Ghaman 2006). The project began in 2002, and the last of four field evaluations (one with each of the four controller vendors) was completed in 2007. A concise summary of the ACS Lite project and findings can be found in Shelby et al. (2008).

As of 2009, ACS Lite was in the midst of a secondary research effort by FHWA to incorporate cycle time adjustment. Currently, cycle length settings are changed according to a time-of-day schedule. Despite this limitation, ACS Lite has been able to produce substantial benefits based on its adaptive split and offset capabilities (e.g., 35% delay reduction in Houston). That being the case, ACS Lite is currently being marketed and deployed as is by the aforementioned controller vendors who participated in the original project.

ACS Lite Architecture

An ACS Lite system is composed of the following hardware:

- An ACS Lite system computer,
- The traffic signal controllers,
- Communications between ACS Lite and the controllers, and
- Vehicle detectors.

In the four field tests—one with each participating controller manufacturer—the exact nature of the system architecture varied somewhat, depending on the manufacturer, as illustrated in Figure A1. More detail is available in Shelby (2008). Each of the four system components is briefly discussed in the following paragraphs.

ACS Lite System Computer

In the interest of the widest possible applicability, FHWA envisioned ACS Lite as being capable of governing traffic signals in either of the following scenarios (Crenshaw 2000):

- ACS Lite could be operated from a traffic management center—such as a traditional central system, or
- ACS Lite could be operated in on-street manner—such as a traditional field master.

In either case, the adaptive control software was to be encapsulated in a single computer, to avoid the expense associated with distributed adaptive systems sponsored by FHWA in the 1980s and 1990s (Luyanda et al. 2003). These earlier non-Lite ACS systems had required that each intersection be equipped with a dedicated processor (aside from that of the traffic controller itself) in order to host adaptive optimization algorithms at each intersection. These prior systems used the 2070 controller, specifically to utilize its unique Virtual Machine Environment (VME) expansion slot, which accommodates the installation of such add-on processors.

Intersection Controllers

FHWA, focused on cost minimization, intended ACS Lite to be compatible with National Electrical Manufacturers of America (NEMA) model controllers, which have historically been less expensive than 2070 controllers, although McCain opted to integrate with its 170 controller (which is generally less expensive). This compatibility enabled deployment of ACS Lite without the need (or expense) for controller upgrades in most of the four field trials. However, in each case, a firmware (controller software) upgrade was required to accommodate support for additional ACS Lite status messages.

Another "intangible" and often overlooked cost saving benefit comes from the capability to retain familiar controller firmware—the core of which is largely unchanged by the communications upgrade. The time and effort that would otherwise be necessary for staff to learn to use and maintain completely new controller firmware could be significant.

Communications

FHWA required that ACS Lite be designed to use National Transportation Communications for ITS Protocol (NTCIP) as its communications protocol, given the desire to encourage adoption of this national standard. It was also specified that ACS Lite be able to communicate over low-speed serial communications, which constitutes the existing infrastructure to most signal controllers at this time. To achieve this goal, custom NTCIP-compatible status messages were developed for ACS Lite to substantially reduce required bandwidth, such that ACS Lite was able to communicate during field trials with eight to ten signals using 9600 baud communications. Higher data rates are necessary to support more controllers. In each of the four field trials, ACS Lite was deployed leveraging existing twisted-pair communications. Modem upgrades were required in some cases; however, this expense compares favorably with the costs associated with installation and maintenance of fiber optic, peer-to-peer communications as has been used in deployment of non-Lite ACS systems previously developed by FHWA. At the time of this

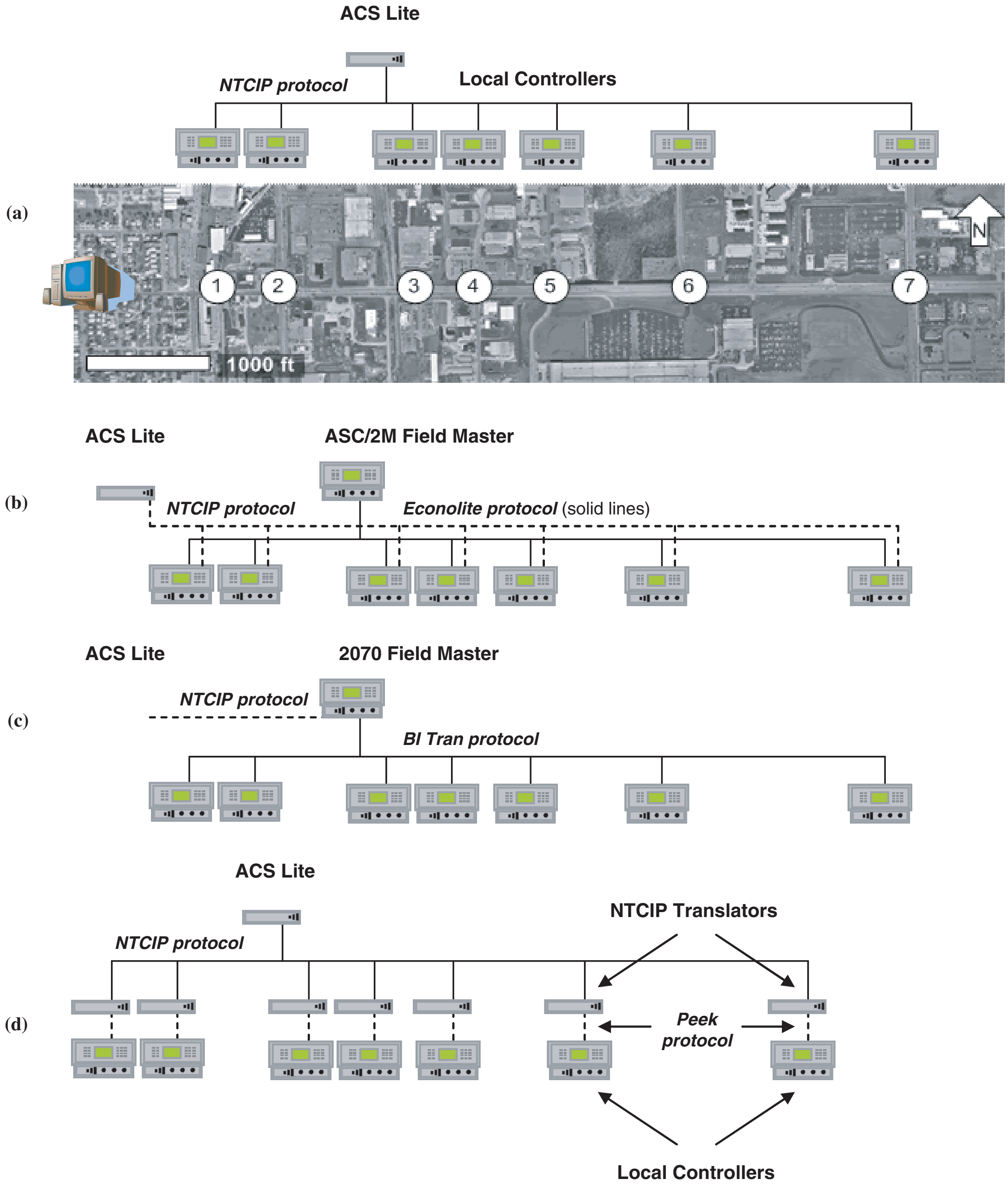


FIGURE A1 ACS Lite as deployed with (*a*) Siemens, (*b*) Econolite, (*c*) McCain, and (*d*) Peek.

writing, ACS Lite supports 16 controllers in a single system. ACS Lite also supports Internet Protocol (IP)-based (Ethernet) communications.

ACS Lite monitors traffic signals by polling each controller on a per-minute basis for time-stamped state changes. If a poll request fails, the status report is still available from the local controller until the end of the minute, so the system has ample opportunity to poll again. This affords a measure of insulation from occasional communication errors, which can compromise systems that require per-second communications. In such per-second systems, a missed poll generally means a hole in the data that cannot be recovered once the 1-s polling window has passed. This appears to be particularly relevant in the context of wireless communications.

Vehicle Detectors

The detection scheme required by ACS Lite is compatible with typical layouts used for intersections under fully actuated control. This reduces the total cost to instrument a typical arterial as required for adaptive control. ACS Lite also incorporates detector processing in such a way as to be relatively flexible with respect to the size, location, and capability of detectors. This capability often reduces the need to resize or relocate existing loop detectors that are in the right location, but are not of ideal dimension. The demand measurement scheme also aims to address concerns that have been raised about the sensitivity of adaptive control performance with respect to precise detector count accuracy.

To adjust splits, ACS Lite requires stop-line detectors for each phase or movement, preferably separated out for individual lane-by-lane monitoring, although lanes serving the same phase or movement may be tied together if necessary. Stop line detectors monitor volume and occupancy on green, and the processing logic accounts or adjusts for the detector length and maximum vehicle speed. Detectors sized from 4 to 70 ft long have shown good results (although 70 ft is generally too long in many scenarios).

On approaches where progression is desired (generally the arterial approaches), advance loops (typically 6 ft × 6 ft) are used to monitor cyclic flow profile, to identify the arrival of platoons, and use these data for adjustment of offsets to improve progression.

Detector processing has been designed to reduce sensitivity to the accuracy of count data. Count accuracy may deteriorate substantially if a loop begins counting axles instead of cars or if video detection cannot precisely separate out two vehicles traveling closely together, owing to the angle of the camera. As examples of "sensitivity reduction," consider that green-occupancy flow measures are less sensitive to errors than pure volume-based flow measures. However, the technique is somewhat more involved than measuring only green-occupancy.

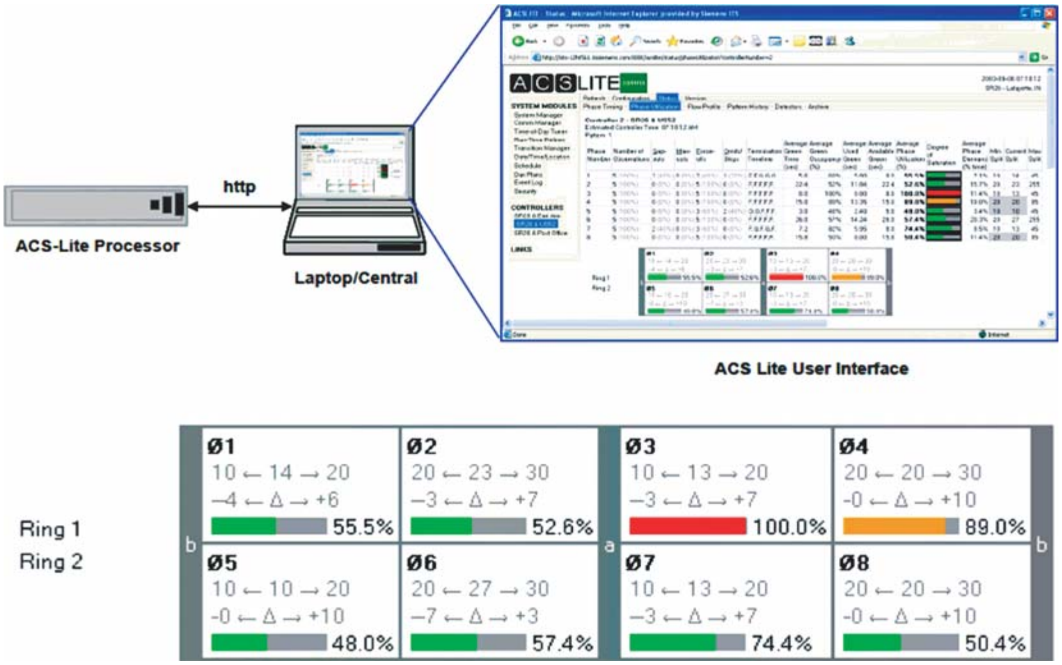
Accurate turning probabilities and saturation flow rates are generally a source of sensitivity (to error) for signal timing optimization. These values are certainly subject to change throughout the day, according to daily travel patterns, and are also influenced by unexpected weather. However, ACS Lite does not require calibration or configuration of these parameters and is designed to gauge traffic demand well over a wide range of conditions (Shelby et al. 2008). Aside from basic verification that a detector indeed works, there is no need for field studies or elaborate detector calibration in ACS Lite. Configuration is limited to known facts, such as the location and dimensions of a detector.

Adaptive Traffic Control Logic

ACS Lite operates by monitoring traffic signals that are running normal, coordinated timing plans and then making incremental adjustments to split and offset parameters as often as every 5 to 10 min. Thus, ACS Lite does not take over second-by-second control of the sequence or duration of each phase, but rather the normal actuated logic allows skipped phases, gap-out, max-out, and/or force-off in a normal manner. Cycle length is currently not adjusted by ACS Lite, although future enhancements are planned. The cycle length is currently dictated by the "underlying" or "baseline" timing plan, which is selected according to the time-of-day schedule (Luyanda et al. 2003).

Split adjustments are based on measures of the "utilization" of each phase (Luyanda et al. 2003). Detector volume and occupancy data are processed, primarily during green intervals, to gauge the amount of time that traffic is flowing across the stop-line. ACS Lite estimates the degree of saturation of each phase. The adjustment logic reallocates split time to balance (with optional biasing) the degree of saturation across all phases, subject to configured minimum green times, pedestrian interval requirements (optionally), and maximum green times (when they are not inhibited during coordination). Thus, time is reallocated from a phase with an excessively long (i.e., underutilized) split time to provide more split time for an oversaturated phase. The split adjustment logic provides an optional "progression biasing" mechanism that distributes "extra" or "slack" green time in the cycle (if it is available) in greater proportion to designated progression phases, which are typically arterial through phases. This option is almost always used, as it has been shown very effective in exploiting the availability of "slack" time to provide a wider green band for improved progression (Shelby et al. 2008).

Figure A2 provides a screen-capture of the ACS Lite's web-based user interface, which provides a color-coded bar chart indi-



Ring 1	Ø1 10 ← 14 → 20 −4 ← Δ → +6 55.5%	Ø2 20 ← 23 → 30 −3 ← Δ → +7 52.6%	Ø3 10 ← 13 → 20 −3 ← Δ → +7 100.0%	Ø4 20 ← 20 → 30 -0 ← Δ → +10 89.0%
Ring 2	Ø5 10 ← 10 → 20 -0 ← Δ → +10 48.0%	Ø6 20 ← 27 → 30 −7 ← Δ → +3 57.4%	Ø7 10 ← 13 → 20 −3 ← Δ → +7 74.4%	Ø8 20 ← 20 → 30 -0 ← Δ → +10 50.4%

FIGURE A2 Monitoring degree of saturation in ACS Lite.

cating the degree of saturation for each phase. These measures are overlaid, in the enlarged view in Figure A3, on a ring diagram, to portray the trade-offs of adjusting split time between phases. This particular screenshot illustrates that phase 3 (a cross-street, left-turn phase using typical NEMA phase numbering) is 100% saturated, whereas all of the main-street phases (1, 2, 5, and 6) are less than 60% saturated. The figure also illustrates that phase 3 currently has a 13-s split, which could be reduced to a minimum of 10 s, or a maximum of 20 s (which allows up to 3 s of room to reduce split time or 7 s of room to increase time).

Oversaturation poses a daily challenge to some intersections. If oversaturation afflicts one phase (or more, but not all phases), then splits will be relocated to alleviate the situation if possible. However, in some cases, oversaturation on one phase (or more) cannot be alleviated with any amount of split reallocation. As this situation develops, ACS Lite will “defend” or “protect” the traffic engineer’s original split timing as follows. Suppose the phase 3 oversaturation in the prior scenario (see ring diagram in Figure A2) cannot be alleviated, despite a substantial reallocation of split time from other phases. This traffic flow scenario has been observed most predictably at shopping center access signals during late November and December. If ACS Lite were to attempt to balance saturation across all phases, then all phases would become saturated and arterial progression would be compromised. To counteract that result, ACS Lite manages phase splits such that no phase is allowed to experience more than 95% saturation with less than the traffic engineer’s original split allocation. For example, if phase 4 was originally allocated 30 s, then ACS Lite might be willing to reallocate some of that time to phase 3, reducing phase 4 to 20 s, so long as phase 4 remains no more than 95% saturated. If traffic flow picks up again on phase 4, such that it exceeds 95% saturation, then ACS Lite will return some or all of its original split time to bring maximum saturation just below 95%, despite phase 3 being oversaturated. The traffic engineer’s original split time allocation for designated “progression bias” phases (generally arterial through phases) will be “defended” at a lower saturation threshold of 90%. Thus, despite oversaturation on a cross street phase, the main street progression phases will not surrender split time to the extent that it approaches oversaturation. This policy has proven effective in alleviating surges in traffic on a particular approach to a reasonable extent, while also protecting arterial progression to a reasonable extent. At intersections that experience oversaturation on a daily basis (often predictably during peak flow), this policy results in splits gravitating back to the traffic engineers original settings, such that the traffic engineer can still dictate behavior in this scenario, and drivers can expect reasonably predictable similar day-to-day service during these periods, which could provide the most reasonably consistent and predictable commute times during these periods.

ACS Lite offset adjustment decisions are based on monitoring advance detectors (and phases) on each approach and averaging data over successive cycles to form cyclic flow profiles (and green phase profiles), which also reveal early-return-to-green behavior. Figure A3 shows a screen shot from ACS Lite, illustrating the cycle flow profiles (blue bars) and green time profiles for all inbound and outbound arterial links of an intersection. ACS Lite adjusts the offset of each intersection in turn, by considering three offset options—keep it the same, adjust a few seconds earlier, or adjust a few seconds later—and selecting the option that maximizes the percentage of arrivals on green for all designated inbound and outbound links.

BALANCE

The traffic-adaptive network control BALANCE started in two research projects supported by the European Union (Munich Comfort and TABASCO). Beginning in 1992, BALANCE was developed at Technische Universität München and later also at the companies GEVAS software and TRANSVER. Since 2002, GEVAS software has been responsible for maintenance and further development of BALANCE. The system has been implemented in several cities including Remscheid, Hamburg, and Ingolstadt.

Adaptive Traffic Control Logic

BALANCE belongs to the generation of the newest German traffic signal control systems. Therefore, it is not relevant whether the existing traffic signals are controlled in fixed-time, traffic-actuated, or with public transport prioritization. BALANCE can deal with any kind of existing control, as long as these can be accessed and controlled by the traffic computer.

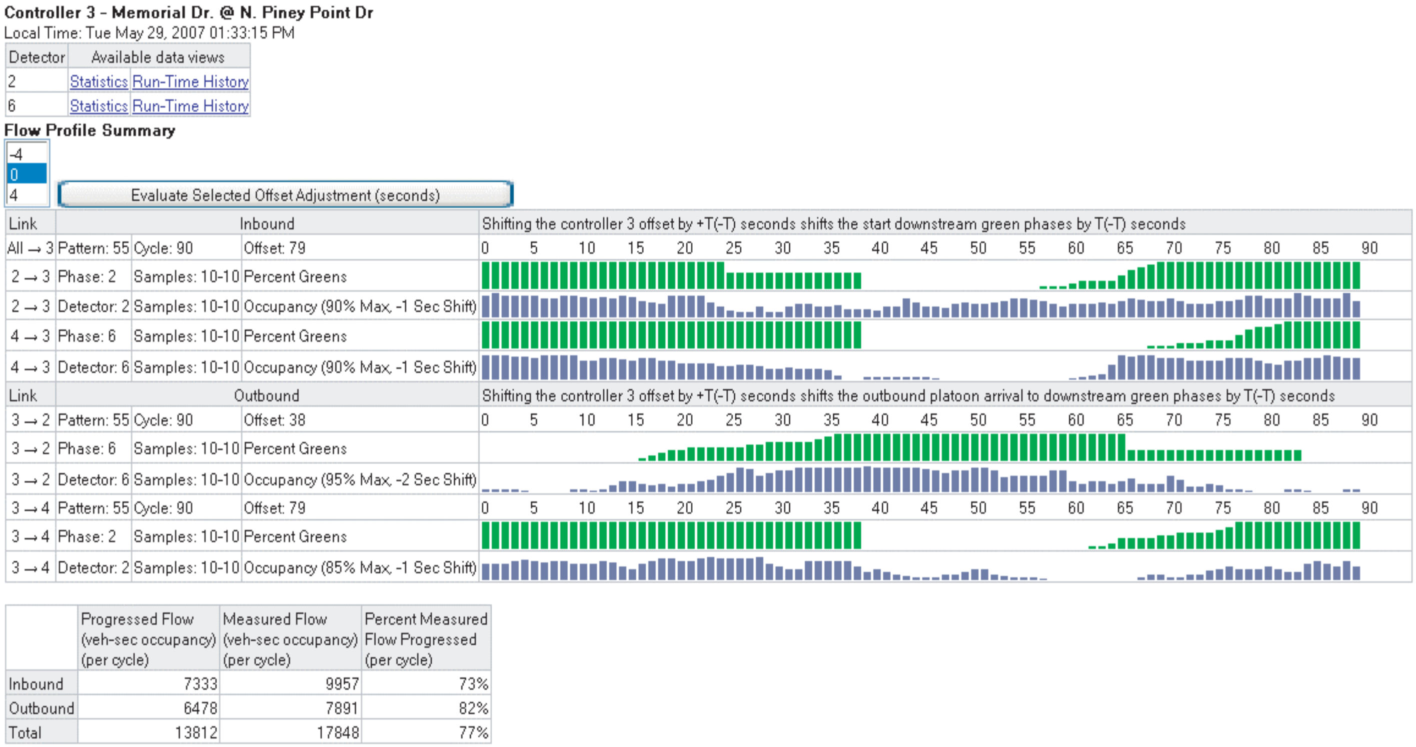
The data packages provided by BALANCE are small and are transmitted only every 5 min. BALANCE’s use of traffic modeling allows for minimal use of traffic detectors. BALANCE will develop optimal signal timings for the existing detection in the field and does not require that every intersection be equipped with detectors.

The basic system architecture of the BALANCE system (shown in Figure A4) divides the functionality for traffic signal control hierarchically on two levels (Braun et al. 2008):

- On the local or operational level for single intersections, the local actuated control reacts on short-term changes in the current traffic demand (every second); and
- On the tactical level of a traffic signal network, the BALANCE algorithm works as a macroscopic system and covers the middle-term and long-term area (5 to 15 min) of the traffic-actuated control.

Minimization of transition times, caused by traffic-actuated signal coordination (offset optimization, green wave), and rough adjustment of release times of the signal groups are done centrally on the network level. Precise adjustment of release times, on the other hand, takes place inside the traffic controller. BALANCE influences traffic light signals in the network by two types of traffic control commands:

- Framework signal plans—for every interstage, the earliest and the latest points at which the interstage could start are defined. The interval between the two points is available to the local, traffic-actuated control for its own local decisions. Apart from these local decisions, the framework signal plan defines the greens at the single signal groups and the coordination of the signal devices.
- Signal program—BALANCE selects the program with the best cycle time for the current traffic situation from a prearranged set of signal programs. The signal program index serves as output date. The selection is done at the same time for all traffic signals of one control group. A control group is defined as a subset of traffic signals in the network (e.g., a group of signals in close proximity).



Controller 3 - Memorial Dr. @ N. Piney Point Dr

Local Time: Tue May 29, 2007 01:33:15 PM

Detector	Available data views	
2	Statistics	Run-Time History
6	Statistics	Run-Time History

Flow Profile Summary

-4
0
4

Evaluate Selected Offset Adjustment (seconds)

Link	Inbound			Shifting the controller 3 offset by +T(-T) seconds shifts the start downstream green phases by T(-T) seconds
All → 3	Pattern: 55	Cycle: 90	Offset: 79	0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90
2 → 3	Phase: 2	Samples: 10-10	Percent Greens	
2 → 3	Detector: 2	Samples: 10-10	Occupancy (90% Max, -1 Sec Shift)	
4 → 3	Phase: 6	Samples: 10-10	Percent Greens	
4 → 3	Detector: 6	Samples: 10-10	Occupancy (90% Max, -1 Sec Shift)	
Link	Outbound			Shifting the controller 3 offset by +T(-T) seconds shifts the outbound platoon arrival to downstream green phases by T(-T) seconds
3 → 2	Pattern: 55	Cycle: 90	Offset: 38	0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90
3 → 2	Phase: 6	Samples: 10-10	Percent Greens	
3 → 2	Detector: 6	Samples: 10-10	Occupancy (95% Max, -2 Sec Shift)	
3 → 4	Pattern: 55	Cycle: 90	Offset: 79	0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90
3 → 4	Phase: 2	Samples: 10-10	Percent Greens	
3 → 4	Detector: 2	Samples: 10-10	Occupancy (85% Max, -1 Sec Shift)	

	Progressed Flow (veh-sec occupancy) (per cycle)	Measured Flow (veh-sec occupancy) (per cycle)	Percent Measured Flow Progressed (per cycle)
Inbound	7333	9957	73%
Outbound	6478	7891	82%
Total	13812	17848	77%

FIGURE A3 Cyclic flows (blue) and green times for two-directional arterial link.

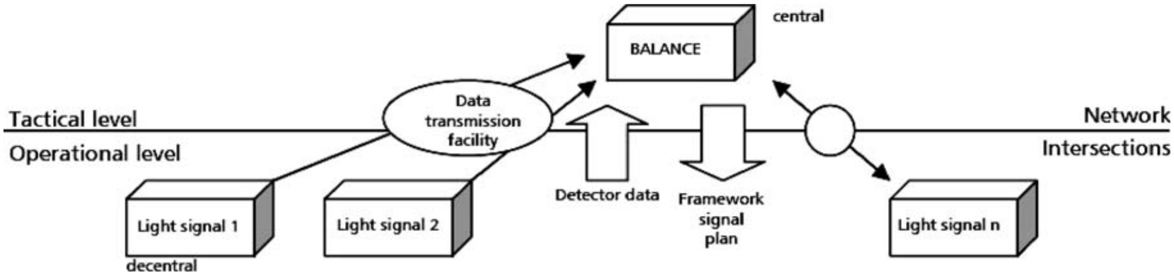


FIGURE A4 Fundamental system architecture in BALANCE.

Traffic Control Optimization

The optimization model of BALANCE network control determines the length of release times (split) and the offsets according to a common cycle length. The optimization is done by Genetic Algorithm, which imitates the process of natural evolution. Interaction between optimization process and field implementation is shown in Figure A5. The final signal timings are achieved over several generations in the constrained time window of 5 min. Although the solution space for the appropriate signal timings is very complex, the Genetic Algorithms have proven that a solution close to the theoretical optimum can be reached (Braun et al. 2008).

The result of optimization is a framework signal plan created for every intersection in the network. A framework signal plan determines fixed or variable signal timings for all traffic signals in a coordinated group of signals. Within given framework plans, local intersection controllers can execute traffic-actuated operations based on the local traffic demand. Priority for public transport is also executed locally.

Detection Requirements

BALANCE can use the data from any type of detectors, regardless of their placement in regard to the intersection. Detection data could be provided in as a disaggregated form as possible so that BALANCE can reconstruct (approximate) the raw detection inputs before the data are further processed. However, transmission of raw detection data requires higher communication capacity than if the data were preprocessed and then sent to a central computer. This need for high-capacity communication media may cause problems for certain communication networks. In such a case, BALANCE can operate with aggregated data, but at minimum traffic volumes and detector's occupancy needs to be provided. It is important that the length of an aggregation interval does not exceed 2 min.

In Germany, traffic detectors are traditionally placed at a short distance (10 to 50 m) upstream of the intersection stop-lines. This type of detector allows good vehicle-actuation operations; however, it cannot be used to estimate input flows and queues in the same way as (far) upstream detectors, or for estimation of saturation flow rates, in the same way as stop-line detectors. To get a good estimation of current traffic conditions a new cycle-based queue length estimation method was developed. This method allows estimating back-up lengths of distances five or ten times greater than the distance between detector and stop-line. The heart of the estimation method uses fill-up time. Time needed to fill-up, with cars, an area between the intersection stop-line and the end of the detector. For that approach, this time is measured from the beginning of the red phase until the detector is continuously

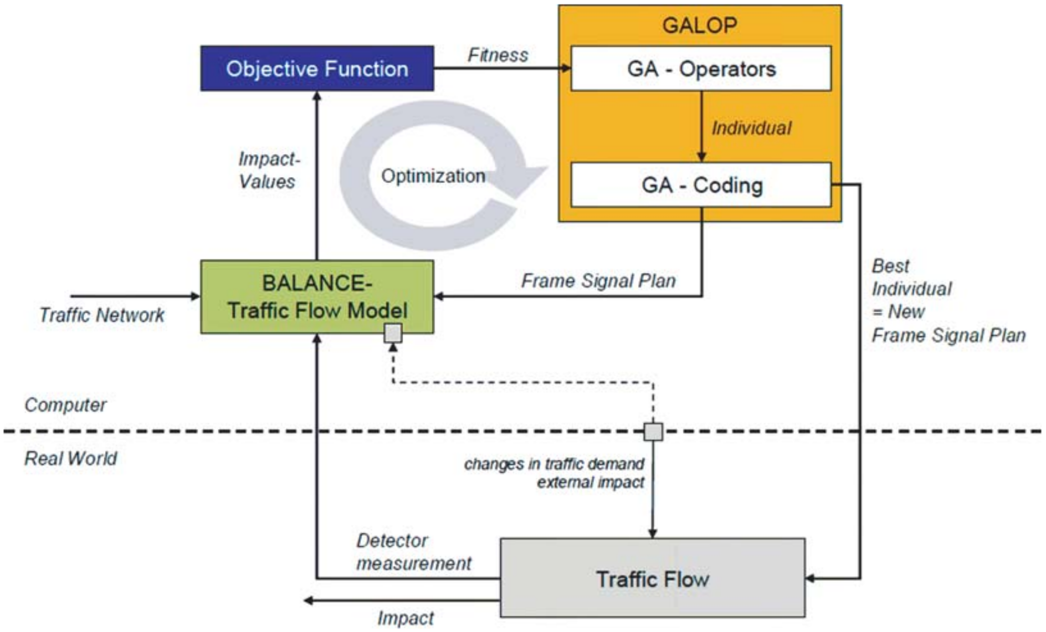


FIGURE A5 Genetic Algorithm (GA) optimization process in BALANCE.

occupied. From the length of this time can be estimated the speed of the vehicles approaching the traffic signal at the end of the green time. A self-calibrating method was developed to estimate queue length based on the fill-up time. This estimation method is a standard way to use detector data for both German ATCSs: BALANCE and MOTION.

Operations

The BALANCE traffic model creates an internal spatiotemporal representation of the current traffic conditions based on the detected traffic loads. The traffic model has two modules: macroscopic and mesoscopic:

1. The macroscopic traffic model estimates the origin–destination matrix between each pair of entries and exits in the network. The origin–destination matrix is based on a predefined weight function matrix and traffic inflows and outflows measured at the borders of the network.
2. The mesoscopic traffic model iteratively takes into consideration current traffic signal status, link travel times, and platoon dispersion factors to develop traffic flow profiles for all links in the network.

A forecasting module of BALANCE estimates impacts of various traffic control strategies for the following time period by calculating performance measures such as delays, stops, and queue lengths for all intersection approaches.

The performance measures are computed with the assistance of both mesoscopic and macroscopic BALANCE models. The mesoscopic model estimates queues at intersection approaches and other deterministic performance measures. Stochastic fluctuations in traffic and origin are estimated through the macroscopic model. The delays from both models are integrated into the calculation of the Performance Index (PI).

The GEVAS software program VTnet/view is used as a visualization interface for BALANCE. VTnet/view displays all traffic parameters computed by BALANCE, such as traffic volumes, link traffic densities, and link level-of-service. Road works and messages posted on variable message signs also can be visualized. Diagrams and journals can be created directly from the visualization interface and can be aggregated for any time period. Two-dimensional display of the network geometry (shown in Figure A6) allows visual control of the supplied detector loops and signal groups during operation.

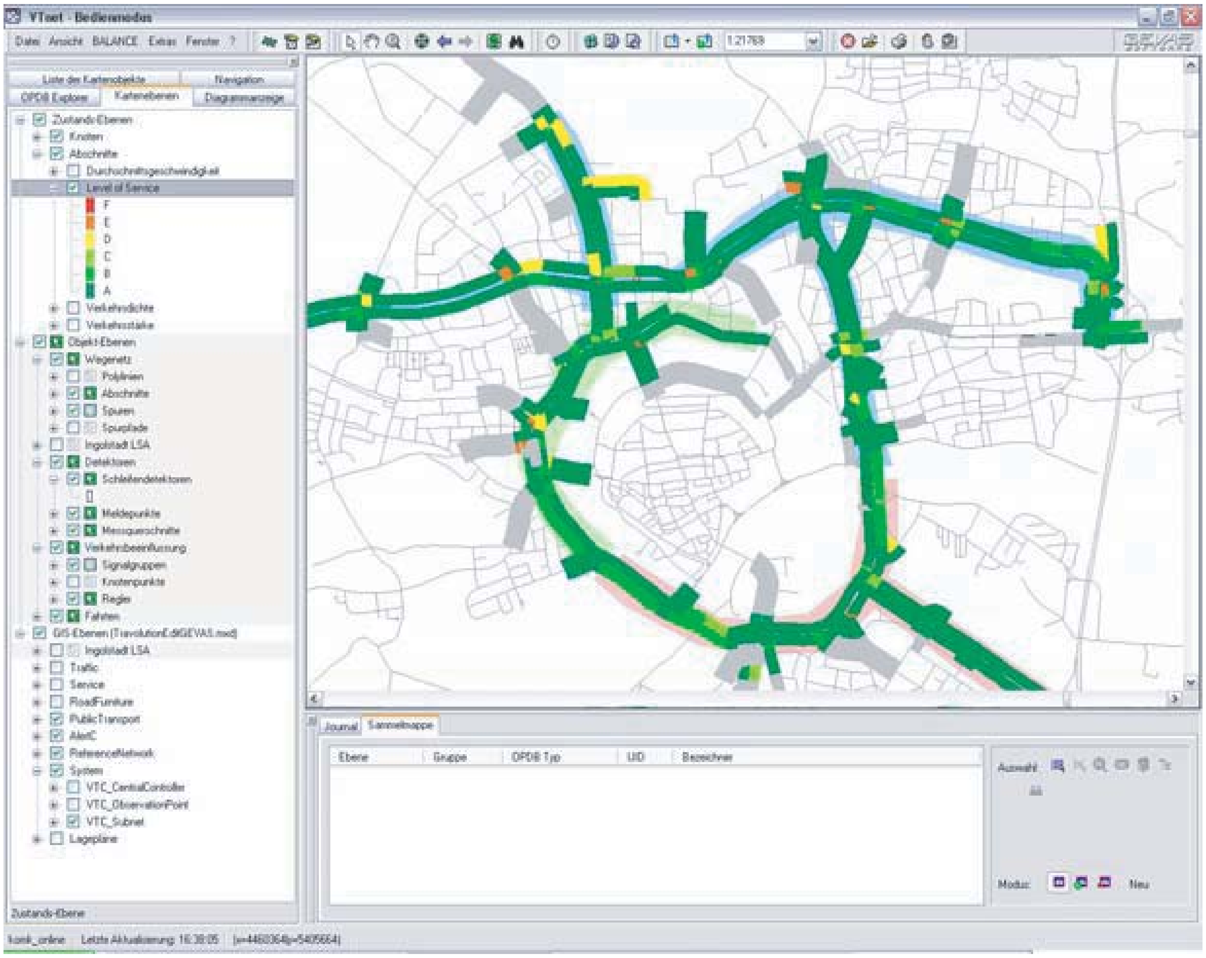


FIGURE A6 VTnet view of traffic load in BALANCE.

Network geometry for traffic visualization in VTnet/view can be taken from all common network formats (e.g., ESRI shape files). Some network elements, such as type and location of turning lanes, detectors, and stop-lines, need to be entered separately. For turning lanes, signal location plans can be displayed as a background image. Detectors and stop-lines can be read from German standard exchange format for signal engineering (e.g., OCIT-I-VD), and then they need to be placed properly on the map. Phases, phase transitions, and signal groups are as well read from standard exchange formats. Follow-up supply of the special parameters required for BALANCE can be done directly in the traffic engineer's workstation CROSSIG.

INSYNC

InSync is an adaptive traffic signal system developed by Rhythm Engineering (Lenexa, Kansas) that uses innovative sensor technology, image processing, and artificial intelligence. These elements are integrated into a system that automatically optimizes local traffic signals and coordinates signals along roadway arterials according to real-time traffic demand. The use of InSync eliminates the need for static signal coordination plans.

Adaptive Traffic Control Logic

There are two aspects to InSync's signal optimization that deal with the conflicting objectives of providing the progression of platoons of vehicles along a main arterial and the clearance of vehicles involved with secondary traffic movements within the grid: the global and the local. InSync operates and optimizes signals within the minimum/maximum parameters that users have input into the initial configuration settings of the system.

The Global Element: Time Tunnels and Adjustable Periods for Optimizing Progression

Users need to determine the main directions within the grid, but can also redefine and automatically toggle between arterials by (Time-of-Day) TOD/DOW (Day-of-Week). Special parameters can be set in for intersecting main arterials that provide effective coordination within the grid.

Time Tunnels Green waves/time tunnels are guaranteed by successively turning each light green at the expected arrival time of vehicles from upstream intersections. This can be illustrated using speed lines as shown in Figure A7. Speed lines are configured starting with a chosen facilitator intersection. By default, the speed lines for the main two directions of travel intersect at this facilitator intersection. Time tunnels are made to occur at this intersection by requiring the simultaneous initialization of green lights for both directions. The facilitator intersection decides a time at which it will serve a green band for the coordinated tunnel phases and communicates that time with the adjacent intersections. Each adjacent intersection uses the expected vehicle travel time between it and the intersection it received the tunnel message from to decide when it needs to turn the tunnel phases green for both its downstream tunnel phase from the facilitator intersection and its upstream tunnel phase to the facilitator intersection. Start times for downstream tunnel phases *to* the facilitator (or upstream *from* the facilitator) at the adjacent intersection

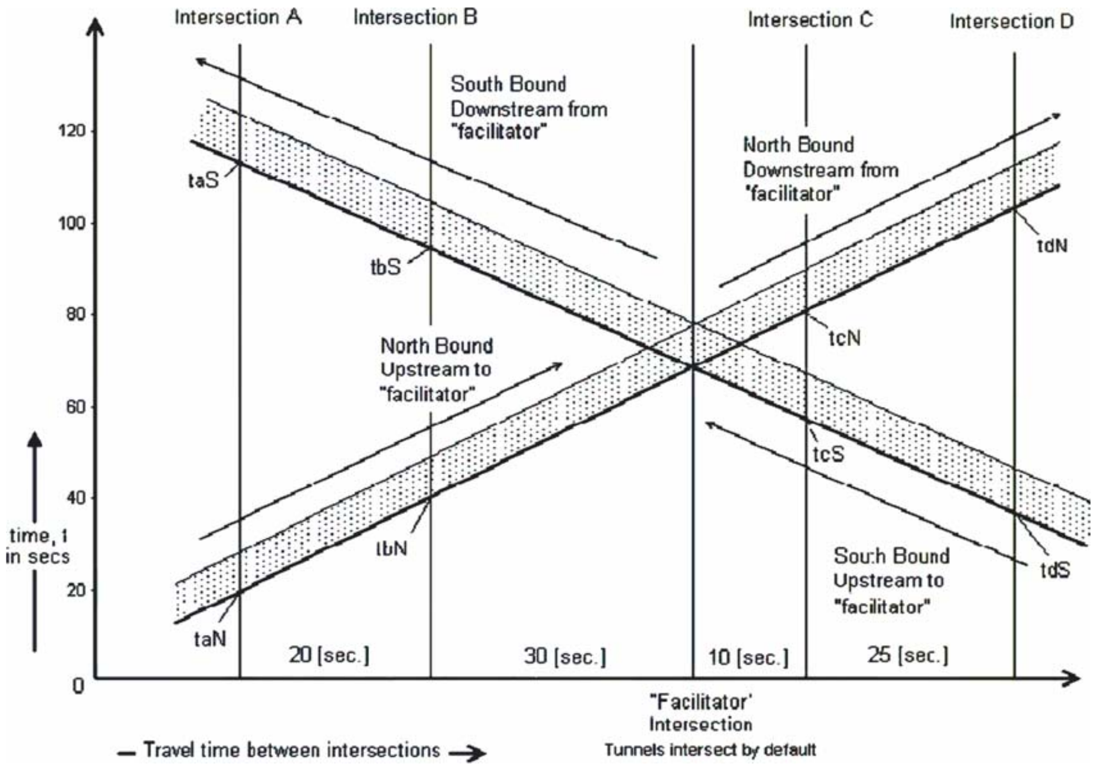


FIGURE A7 Concept of "Time Tunnels" in InSync.

are adjusted by (− travel_time) so that vehicles are released from the upstream intersection in time to reach the facilitator intersection when it initiates its tunnel time. Start times for downstream tunnel phases from the facilitator (or upstream to the facilitator) at the adjacent intersection are adjusted by (+ travel_time) so that vehicles are released from the downstream intersection as they arrive from the facilitator intersection.

Using the travel times between each adjacent intersection these tunnel times are calculated by each intersection as it receives the dynamic tunnel phase timing messages from each adjacent intersection along the artery. Visually, the speeds lines for an artery with two main directions of north bound and south bound with four "listener" intersections and one facilitator intersection in the middle would look like this:

Expected travel times between intersections are listed on the x-axis, and elapsed time is the y-axis. The slope of a speed line is always 1, because the expected travel time between intersections has a 1 to 1 relationship with wall time (or time on a clock).

Tunnel start times at each intersection for the north and south phases are relative to the tunnel start times at the facilitator. If we say that the north and south tunnel phases start at $t = 0$ at the facilitator intersection, then *t*cN (the time of the start of the north bound downstream tunnel phase at Intersection C) = 0 + travel_time_to_facilitator = 0 + 10 = +10. This says that Intersection C needs to force a green light for the north bound phase 10 s after the facilitator intersection does. *t*cS (the time of the start of the south bound upstream tunnel phase at Intersection C) = 0 − travel_time_to_facilitator = 0 − 10 = −10. This says that Intersection C needs to force a green light for the south bound phase, 10 s before the facilitator intersection does. To complete the example, the other start times at Intersections A, B, and D are:

*t*dN: +35
*t*dS: −35
*t*bS: +30
*t*bN: −30
*t*aS: +50
*t*aN: −50

Additionally, the speed lines are not actually required to intersect at the facilitator or even intersect at an intersection. The tunnels can be offset to allow any arrangement of speed lines as desired. This flexibility can provide for more efficient progression. Also, travel times for both directions between adjacent intersections do not have to be the same. The south bound direction may take 5 s longer to travel than the north bound direction between two intersections. The minimum tunnel bandwidth (or guaranteed green time for a tunnel phase) is configurable.

Vehicles traveling along the main arterial that arrive at an intersection at the beginning of the time tunnel ideally progress unstopped all the way through the coordinated arterial. InSync automatically extends green lights beyond the set parameter if it observes that the moving platoon has not sufficiently gapped out at a user changeable percentage of occupancy (calculated every second by InSync) or set gap time. InSync may, if permitted by the user, provide a green light along the main street before the light is guaranteed to be green. Real-time traffic data are continually passed to downstream processors by their upstream partners that can also be factored into the optimizing process.

Intelligently Adjustable Periods Through its global interactive communications with the intelligent processors at each intersection (also see the next section: The Local Element) the facilitator will, if necessary and as soon as possible, expand or contract the time between tunnels to provide the optimal period lengths to serve each phase along the arterial. At the end of every period, each local processor is "polled" by the facilitator and "reports in" if it needs more time, the same time, or less time to clear its local phases. These period length adjustments serve to efficiently progress vehicles and clear out queues, both globally and locally.

The Local Element: Logic and Features of the Optimization Algorithm

Beyond the constraints communicated by the facilitator as "tunnel messages" that guarantee coordinated green lights for the main arterial, the signals operate in "intelligent fully-actuated" mode. The time between tunnels is called a period. If a period is 90 s in duration and a green light is guaranteed for the main directions at each intersection for 10 s, then 80 s are available for the local optimizer to schedule states (phase pairs) at each intersection according to its intelligent scheduling. The local optimizer embodies the dominant logic and algorithm of the adaptive capacities of the system.

Scheduling of States There are three main factors the optimizer considers in its scheduling logic:

1. If it is close to the initiation of a new tunnel, it will schedule a main street sequence of states. This sequence of main states is only allowed to be scheduled such that after it completes there is sufficient time to schedule a sequence of cross street states. If the main direction requires a leading left turn, its clearance time is also included in the calculation for time needed on the cross street.
2. If a tunnel has recently ended, it will schedule a cross street sequence as its priority. The amount of time needed for the cross street is based on a balance between the actual amount of clearance time needed and anticipated time needed. If there are no cross street queues it will schedule a miscellaneous main state.
3. A miscellaneous main state is scheduled for phases with queues that have been waiting the longest. Wait times being equal, the phase with the largest queue is scheduled. Any available miscellaneous time is used to schedule any phase with real-time demand including protective permissive left turns on the main directions.

Empty Queues In the calculation of a state sequence every vehicle phase is assumed to have a queue of 1 vehicle, if no queue exists. These phases typically find their way into the states scheduled toward the end of the state sequence. This way, if vehicles do arrive on these previously empty phases, they can be served. In this sense, those states act as place holders for vehicles that may arrive. If a phase remains empty when it becomes time to serve that state, that state is either removed or modified to contain phases that do contain a queue of vehicles.

Duration of States After an initial sequence of states is scheduled, the durations of each state are continually modified to contain enough clearance time to serve vehicles that may have arrived after the state was initially scheduled. As each previous state in the sequence reaches extension time, all states scheduled after adjust their initial durations for newly arrived vehicles. Adjusted durations and extensions are limited by the amount of time left to serve vehicles on pending phases. For a state with two phases, *ph1* and *ph2,* if *ph1* clears out, a phase concurrent with *ph2* that has a queue can be put in place of *ph1,* assuming there is enough time remaining in the scheduled state to fulfill the new phase's minimum green time, amber time, and red time.

Termination of States States being served are ended or dynamically modified as phases are terminated. Termination of a phase occurs in one of two ways. Both of these methods employ a model of linear change with time, such that a phase will terminate at a higher percentage of capacity as time increases or the phase's gap time will decrease to a point at which, once presence for a detection zone is lost, the phase will terminate as time increases.

Calculating a Sequence The optimizer gathers the data for the calculation: current queues, pending pedestrian calls, and any upcoming plans for tunnels. These requirements are converted into restrictions on the beginning and ending times of green lights for phases. A queue is converted into a minimum clearance time: the ending time minus the beginning time for the phase must be at least equal to the time to clear the queue plus the change time required for that light to turn green; similarly for a pedestrian call, except that the clearance time is the time required for pedestrians to walk across the intersection. A plan for a tunnel is converted into restrictions on the beginning and ending times for the phase: the beginning time must be less than or equal to the beginning time of the tunnel minus the change time, and the ending time must be greater than or equal to the ending time of the tunnel. The optimizer considers each permitted sequence as a sequence of transition times at which phases begin and end, with the restrictions transformed into inequalities in these transition times. For each sequence, a minimum-total-time solution satisfying these restrictions and the total waiting time for queues are calculated. The sequence with the least total waiting time is chosen. If no solution satisfying the restrictions exists for any permitted sequence, then the lowest priority of the restrictions are relaxed until a solution is possible: first, queues on permissive left turns are transferred to their adjacent through movements, then the queues with the least waiting times have their clearance times reduced, then, finally, only the plans for tunnels are considered. Once a solution is obtained, the times are translated into a schedule of states and the first state of the schedule is initiated.

Early Release Sometimes, it is useful to prevent cars from leaving an intersection too early and collecting at a downstream intersection, either because there is a limited amount of space available for cars to queue or to absolutely ensure that the downstream light is green when they arrive. This is sometimes called metering. To handle these situations, the optimizer has the configuration option of restricting early release of a tunnel phase at an intersection.

Period Length Evaluation During local optimization, the intersection continually analyzes its queue lengths and percentage of occupancy for each phase. If the intersection determines that it has not been given enough overall time to adequately clear out its queues (drop the percentage of occupancy to a desired threshold), the intersection reports this to the facilitator (see the previous section: The Global Element). This method of adjusting the period is reactionary. To be more proactive, each intersection constantly analyzes the flow rate of vehicles in each phase. If the current flow rates over the past 15-min durations are comparable to the historically logged flow rate, then it is assumed that the current pattern of traffic can be served using a period that was adequate enough to serve the historical pattern of traffic. This process is known as period prediction and is communicated to the facilitator intersection along with the real-time load analysis of the local intersection. The facilitator intersection uses all of this information to determine if/how it will adjust the current period.

Digital Signal Control Concepts—Finite Number of Signal States (No Transition)

InSync does away with set cycle lengths, set splits, and offsets to a fixed point in the cycle that have traditionally been considered essential for signal coordination. These concepts are germane to a linear/analog approach to signal coordination. InSync is an artificially intelligent/digitally based finite-state changing machine. By its method of externally influencing a controller it causes any controller to effectively function digitally. This digitization does not refer to the nature of the component parts of the controller, but rather a "digital methodology" of how traffic signal phases are chosen. In relation to traffic movements, there is a maximum of 16 possible sequences of phase pairs (states) at any quad intersection. Because it knows the real-time traffic demand, InSync is able to instantaneously select and input to the controller any user-permitted phase pair associated with these 16 sequences that it deems optimal. InSync needs to decide: (1) optimal sequence, (2) when to initiate a state (phase pair), and (3) duration of that state.

It is not limited in its choices or their duration times by a set cycle length, split, or offset. Except for minimums and maximums and 1 s passage times, all typical volume density inputs to the controller are disabled so that it runs in free mode. This permits the controller to quickly react to and change the traffic signal according to the optimized calls coming through InSync. Another important advantage of this "state-changing" architecture and methodology of signal optimization is that the traffic flow disruption caused by the transition from one static timing plan to the next, or by preemptions, is eliminated.

Hardware and Software Requirements

Hardware Overview—Cameras, Processor, Detector Cards, Ethernet Communications

InSync uses high-end IP digital cameras in weatherproof enclosures that are normally mounted on mast arms with standard brackets. The cameras are connected to an InSync processor installed within each local traffic cabinet through a CAT-5 Ethernet cable and a 24-volt electrical wire that provides power. The InSync processor is placed in the local traffic cabinet and interfaces with the local signal controller using detector cards that are plugged into existing detector card racks. Other system hardware includes a 110/24-volt transformer, surge protectors, an unmanaged Ethernet switch, and a pigtail cable for red/green returns to be fed back into the processor from the controller's leads. Except for an I/O board within the processor and the associated detector cards that are each required to communicate with the various proprietary controllers, the system uses off-the-shelf components. For arterial coordination to take place, Ethernet communications need to exist between the networked intersections. Because InSync uses distributed network architecture, an unlimited number of signalized intersections may be coordinated.

Configuration Procedures—Standard Web Interface

InSync is both Ethernet and web-centric in its functionalities. Each processor and every camera has an IP address. These components can be accessed directly by means of the network without any proprietary software. All the necessary configurations of and any software upgrades to the system software can be accomplished remotely over the Ethernet network. The onsite cameras are properly aimed, zoomed, focused, and tightened to effectively view vehicles arriving at and progressing through a traffic signal. A web page associated with the InSync system is accessed through a standard Internet browser (Internet Explorer or Firefox) that leads a user through the process of drawing all the necessary detection, count, and contrast zones that quantify the traffic data generated by approaching vehicles. It also provides a dropdown menu page for all the adaptive system parameters.

Interface Methodology—Determination of Inputs Optimized Calls to Signal Controllers

InSync is a plug-in technology that interfaces with all existing traffic signal controller and cabinet architectures. It controls traffic signals by submitting calls to the traffic controller through detector cards, just as inductive loops do. However, InSync only allows one phase pair at a time to be input to the controller by filtering, prioritizing, and suppressing the demands generated by the detection of vehicles that are approaching an intersection in real time. Pedestrian calls are also filtered by InSync and are permitted at the times deemed optimal by InSync's real-time coordination. InSync's calls are passive in that InSync will yield to any higher priority calls that are directly communicated by users' choice into the controllers; that is, preemptions or central system software priorities. In these cases, InSync will continue to serve as a detection device and then revert to its optimization mode when the controller begins to respond to its calls again. It can also be configured to toggle automatically between detection mode and optimization mode by TOD/DOW if users desire to use predetermined timing plans.

Detector Requirements

The video/data collection sensors (the IP cameras) capture and communicate real-time images of vehicles approaching an intersection to the InSync processors. The processor reads and interprets these images for its optimization processes. This kind of image tracking provides a sufficient estimation of real-time queue lengths and the percentage of occupancy of each lane and approach for optimization purposes. Advanced detection is not essential to create an effective traffic-adaptive dynamic, although it can be incorporated seamlessly into the system. These data are updated by the processor every second. (Similar traffic data could also be input using other kinds of sensors.)

Failure Mitigation

When a sensor is placed in emergency/fog mode, InSync will access 4 weeks of historic green split data for specific TOD/DOW at that particular approach. These data are normalized into a split time to put in to the controller until the sensor is functioning again. A call is issued for every phase for at least a minimum split time, which happens in the following cases:

- A camera fails to talk to a video processing detector subsystem.
- The video processor determines the view is not sufficiently clear.
- The processor does not hear from a particular detector subsystem. A text alert is seen on the video image when a sensor is in emergency/fog mode.

Calls on all phases are automatically input when:

- InSync determines that the detected traffic is significantly lower than historical averages, which indicates a sensor failure.
- The I/O board fails to hear from the processor for 2 s.
- A detector card fails to hear from the I/O board for 2 s.

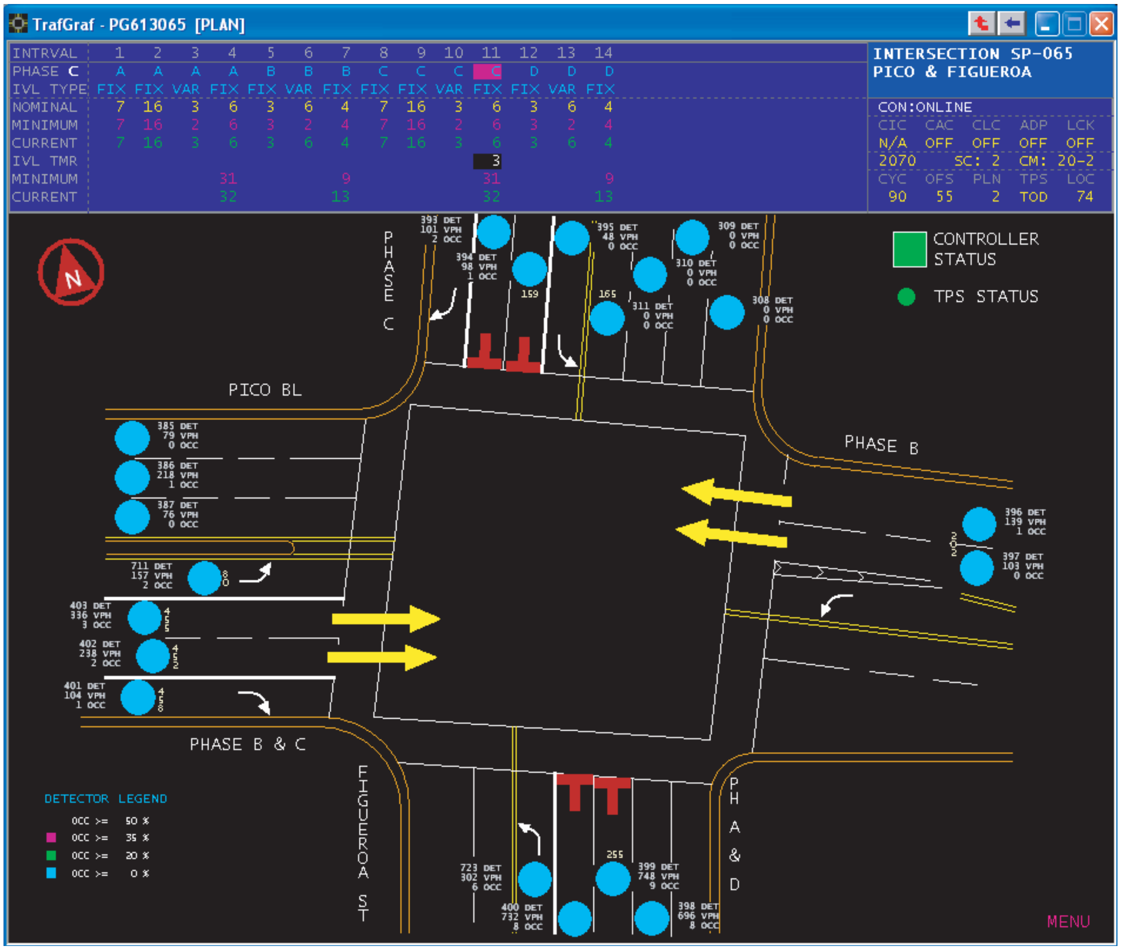
If communications between networked intersections fail, individual processors will continue to perform local optimization functions.

LA ADAPTIVE TRAFFIC CONTROL SYSTEM

The Adaptive Traffic Control System (ATCS), developed by Los Angeles Department of Transportation (LA DOT), was first deployed as a part of the Automated Traffic Surveillance and Control (ATSAC) Center in 1984 for the Los Angeles Olympic Games. Prior to the implementation of the ATCS, the heart of the system was a group of mainframe computers that communicated with both the control center operators and traffic signal equipment in the field. The software used by the mainframe computer was the Urban Traffic Control Software (UTCS) on an OS/9 real-time operating system. Funding for the system was provided by the city of Los Angeles, Los Angeles County Metropolitan Transportation Authority (LACMTA), and FHWA (Hu 2000).

Adaptive Traffic Control Logic

One of the primary goals of the LA ATCS development team was to develop an open system that can be used to test various control algorithms. The basic principle of ATCS adaptive operations is to adjust signal timings on a cycle-by-cycle basis by changing cycle length, splits, and offset. Optimizers for splits and offsets are called in ATCS "Critical Intersection Control" and "Critical Link Control," respectively. Each optimizer can function independently of others. The system allows for maximum flexibility when individual intersections are assigned to various sections (groups of signals). ATCS is a very responsive system that can respond to spikes in traffic demand. On the other hand, the system has some attenuating features that help the system avoid overreacting to short-term variations. LA ATCS does not perform any optimization when adjusting basic signal timings; however, it applies heuristic formulas based on extensive operational experience. Critical link and critical intersection approaches are used to calculate intersection splits and offsets. ATCS configuration parameters can be easily adjusted to adapt to different street configurations. The adaptive adjustment of signal timings is based on changes in volumes and occupancies, which are collected every second but utilized every cycle. The system allows for limitation in variation of cycle lengths by providing its upper and lower limits. When splits are adjusted minimum phase green times are considered. LA ATCS does not alternate phase sequence, which is fixed all the time, but phases can be omitted based on the existing traffic demand. Figure A8 shows a Dynamic Map functionality in



TrafGraf - PG613065 [PLAN]

INTRVAL	1	2	3	4	5	6	7	8	9	10	11	12	13	14
PHASE C	A	A	A	A	B	B	B	C	C	C	C	D	D	D
IVL TYPE	FIX	FIX	VAR	FIX	FIX	VAR	FIX	FIX	FIX	VAR	FIX	FIX	VAR	FIX
NOMINAL	7	16	3	6	3	6	4	7	16	3	6	3	6	4
MINIMUM	7	16	2	6	3	2	4	7	16	2	6	3	2	4
CURRENT	7	16	3	6	3	6	4	7	16	3	6	3	6	4
IVL TMR											3			
MINIMUM				31			9				31			9
CURRENT				32			13				32			13

INTERSECTION SP-065
PICO & FIGUEROA

CON:ONLINE

CIC	CAC	CLC	ADP	LCK
N/A	OFF	OFF	OFF	OFF

2070 SC: 2 CM: 20-2

CYC	OFS	PLN	TPS	LOC
90	55	2	TOD	74

FIGURE A8 Dynamic Map shows intersection details in LA DOT ATCS.

LA ATCS, where operational characteristics of an intersection can be monitored in real time.

Hardware and Software Requirements

The ATCS system, which was fully implemented in 2003, replaced the Concurrent Computer Corporation mainframe with an Intel/Windows NT-based server. The four terminals were replaced by a single Intel/Windows 2000 personal computer (PC) workstation connected to the server through the Ethernet network. Operators control and command the network using the ATCS Client on each PC Workstation. Network and traffic signal information is displayed through graphics in the ATCS Client. Information between the PC workstation and the server is carried by the Ethernet network. The ATCS Kernel is the heart of the system. It is the ATCS Kernel that provides, on a second-by-second basis, for the ability to issue timing change commands, the computation of automated timing adjustments, and the capability of the system to send information to the operator. The data flow between the Kernel and the field is managed by the Data Server (DS), which is the next critical piece of software running on the server (*Adaptive Traffic Control System* 2006).

Besides switching to commodity equipment, ATCS was written using commercial grade C++. All elements of the software, except for the Kernel, were written to be Object Oriented. This allows for easier changes to be made to the software, thus giving it the unique ability to change over time. The server also provides information to a central 'supervisor' machine that uses the data to update the Softgraph graphics display. The supervisor machine also provides the external time source to all other machines to maintain synchronicity. Time data are also received by means of a radio from the WWV transmitter in Colorado Springs, Colorado.

LA ATCS central software can be interfaced either with Type 170 controllers, in which case BI Tran Systems 172.3 software is used, or with Type 2070 controllers, which utilize city of Los Angeles Traffic Signal Control software. In any case, central hardware is a rack-mounted server with a backup PC. Workstations have two 21-in. monitors and multi-port PCI serial cards (Peripheral Computer Interconnect). The system runs on an Ethernet network.

System Architecture

In LA ATSC's system architecture (shown in Figure A9), the centralized area computer (PC server) communicates to local controllers. The communications between elements in architecture use multi-port serial cards that are connected to communication

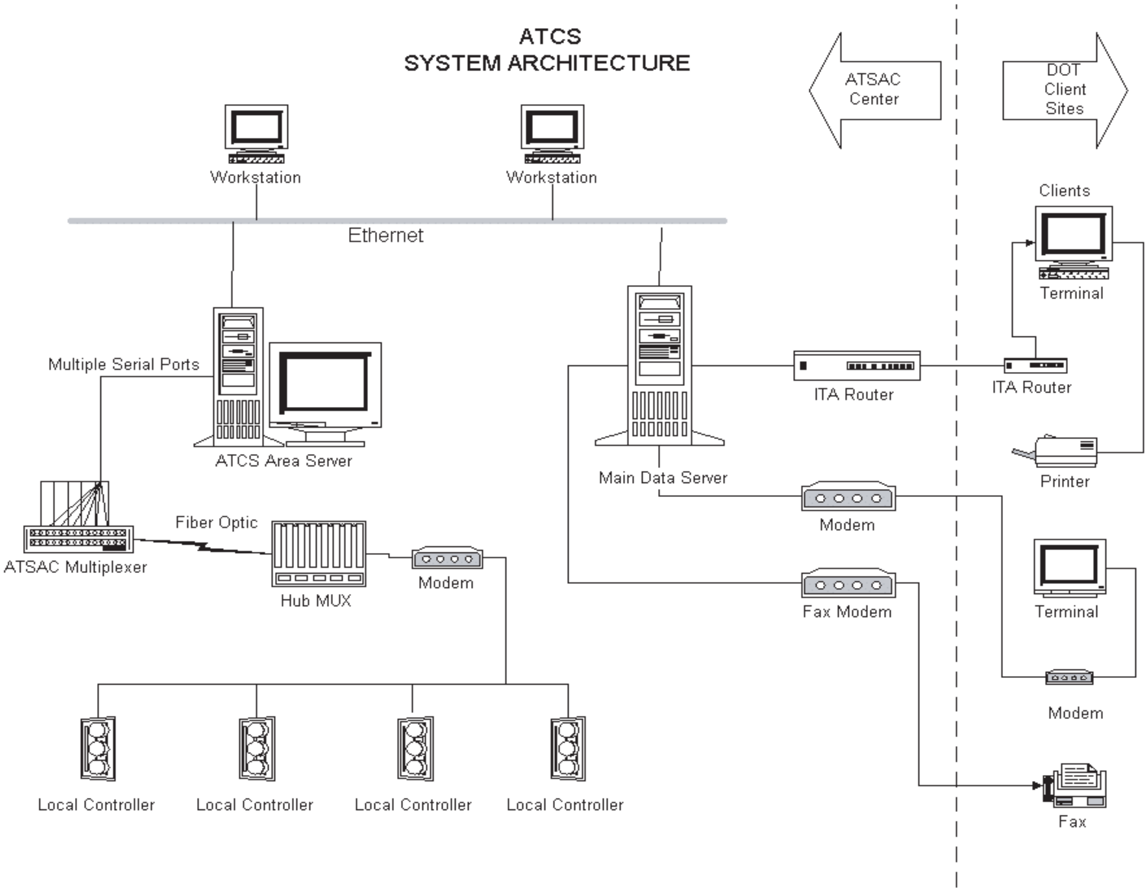


FIGURE A9 LA DOT ATCS system architecture.

lines. All area computers and workstations are interfaced though a Client Graphical User Interface (GUI). The architecture represents a distributed client–server system, which can handle up to 400 intersections and 6,400 detectors per system. Currently, LA ATCS operates approximately 4,300 signalized intersections with approximately 3,000 of them running adaptive control logic (Hu 2000).

One of the most significant recent improvements in ATCS is the development of the Area Server. Instead of a large mainframe with terminal servers, which were originally deployed, the core function of the control system is now handled by a commercial-grade computer with off-the-shelf client workstations hooked up to it. Significant reduction in deployment cost is realized with this design along with an expanded base of knowledge for maintenance.

Detector Requirements

LA ATCS requires at least one detector per lane for each phase. Detectors are usually located 200 to 300 ft upstream of the intersection, which allows the system to collect a set of useful traffic metrics such as volume, occupancy, speed, stops, queue, and delay. ATCS has features that enable the system to identify and screen out bad detectors. Traffic demand at the detectors is smoothed before being used to project new cycle lengths. If detector data are not available, phase splits are prorated based on fixed-timing plans stored in the ATCS databases.

Communications

LA ATCS uses dedicated communication paths between host and local controllers. Time division multiplexing is used in the communication between elements in the network. Local controllers are polled once per second at 1200 bps. In this way four intersections can be handled per communication line. Multiple communication protocols are allowed. Download and upload features between the central system and local controllers are supported.

Communication from the field 170 and 2070 Traffic Signal Controller is accomplished by the way of a 1200 baud twisted pair to a local area hub, terminating in a GDC Corporation multiplexer. From the multiplexer, the information is sent through a fiber optic SONET loop to the server in the ATSAC Control Center.

Detector data from the field are processed on a second-by-second basis. Timing plans are created and maintained as ASCII files, which are compiled into binary format and used by the server to change timing plans. Force Off commands are used by the server to cause the controller to move into the next timing interval.

Special Features

LA ATCS applies a set of logics to handle oversaturated traffic conditions in its network. For isolated intersections this logic usually means an increase in cycle length, which is triggered by high-occupancy data. Green splits are adjusted based on phase demands. For major arterials the logic for oversaturated conditions identifies critical link(s) and provides progression for the congested approaches to reduce oversaturation both temporally and spatially. For minor intersections the system runs double-cycled operations to reduce unnecessary delays.

LA ATCS uses loop-transponder technology to detect buses and provide transit priority. The system checks bus schedules in the central database and if the bus is late it provides green extension/red truncation for the late bus. LA ATCS is capable of calculating bus arrival time, which is used to determine the extension time and minimize adverse impact on cross streets traffic.

MOTION

MOTION represents one of the systems developed in Germany as a response to permanently increasing traffic loads in German cities, something that previous traffic-actuated control was not able to cope with. In a way, MOTION (along with BALANCE, another German ATCS) represents a "German ATCS," where an ATCS is developed to accommodate use of the existing infrastructure. As such, MOTION is developed to work around inherited problems such as a limited number of detectors that are not placed optimally to gather necessary microscopic data to catch changes in cyclical patterns of traffic flows. Instead, existing detectors are used to estimate performance measures that are used to estimate state of the traffic in the entire region. With an increase in traffic flows, MOTION will detect the change through the estimated state of the traffic and will suggest change of the signal timings to accommodate the change in traffic flows. The entire feedback mechanism works in a 5- to 15-min framework, which allows utilization of existing communications without the need to install fiber optics or other high-tech and expensive communication media. Local controllers continually take care of traffic at individual intersections buy applying common traffic-actuated logic (Mueck 2005).

Adaptive Traffic Control Logic

Within MOTION cycle time, split and stage selection is calculated to achieve favorable and balanced saturation levels for all intersection approaches. In this way, excessively low utilization (with high delays for concurrent movements) and excessively high utilizations (that can lead to oversaturation and congestion) are avoided. Selected links in the network can be assigned higher priority through specific weighting parameters; for example, main corridors or roads used by trams and buses. Coordination is optimized afterwards by using models of delay and a number of stops for all flows, applying an objective function that allows individual link weightings. Additional specifications on the priority of the flow and offset times can also be manually fixed in order for example to consider ancillary operational conditions of closely adjacent signal systems.

First experiences with adaptive network control in Germany resulted in the awareness that additional operational functionalities could be integrated in ATCSs. ATCSs would be able to react to severe incidents by special far-reaching measures; for example, to dissolve congestion caused by serious accidents. MOTION has an internal strategy management that allows for an extensive reaction to special operational situations. Those situations can be either automatically identified by internal sets of conditions or by input from the traffic management center. This strategy management allows for individual configuration of all important optimization parameters, such as signal timing plans, minimum and maximum green times, stage sequences, and all sorts of weightings.

The main difference between MOTION and conventional ATCSs (such as SCOOT, UTOPIA, SCATS) is that the operational second-by-second control of the signal groups is separated from the adaptive control level. Instead, controllers are in charge of the operational decisions, whereas the adaptive logic (on the network level) updates controllers every 5 to 15 min with new framework plans (Mueck 2008). This approach brings the following benefits to the concept of adaptive traffic control:

- There is no need for traffic state estimation on a second-by-second basis. State estimation algorithms can be based on the data aggregated per minute or per cycle.
- Missing detector measurements can be replaced by methods using averaged values without the need to model them in on a second-by-second basis.
- There is enough time for central processing units to run extended algorithms for the optimization for a network-wide coordination.

System Architecture and Communications

MOTION is positioned as a tactical component in the overall management of traffic signals. MOTION receives data from the detectors and traffic information from an existing city-wide traffic management system and returns adapted signal timing plans to the local controllers every 5 to 15 min (as shown in Figure A10). Because MOTION is aware of what is going on in the entire region and not only at the intersection whose signal timings are being modified, it improves the quality of the signal timings and consequently improves traffic performance on the roads (Mueck 2008).

Network state information can be provided to the local controllers. For example, queue lengths and delay times estimated by the network optimization module can be used to determine local transit priority strategies to better synchronize private vehicles and public transit.

The internal traffic model allows for area-wide optimization (theoretically), reaching a system-wide optimum. Optimization can be configured according to specific demands such as minimum environmental impact or maximized journey speeds. Undesirable dynamical effects are avoided, because they can occur when optimization is done on a step-by-step procedure from controller to controller.

Internal forecasting algorithms allow for the optimization of cycle time, split, and offset under consideration of upcoming queuing back phenomena, as well as blocking and gating mechanisms.

The cycle time, offset, and split optimization algorithms are highly configurable. It is easily possible to correspond to regional traditional design patterns and planning standards. Sophisticated configuration patterns and models allow for responding to local geometrical or operational requirements and restrictions.

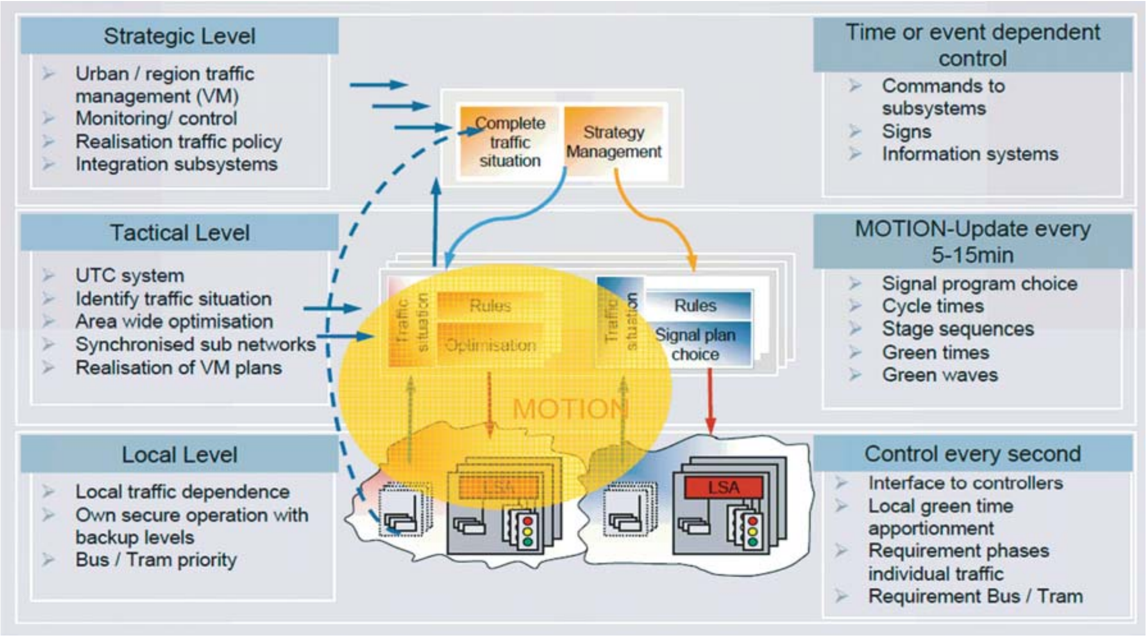


FIGURE A10 Overview of MOTION operations.

A fast and efficient internal strategy module allows for a quick and network-wide response to traffic incidents. It increases the effectiveness of the network control in areas around trade fairs, airports, and shopping centers, which characteristically have fast-changing traffic conditions and a high risk of incidents. The strategy management is an adequate interface to highway or parking systems and can be integrated with city-wide traffic management centers.

Local real-time adaptive behavior is handled by the local controller. The local second-by-second actuated-traffic control of each intersection is still monitored by traffic engineers and carried out autonomously by the individual controllers. As a result of the use of local detectors a fast reaction to microscopic traffic changes by traffic-actuated stage length regulation is guaranteed. This works even in the case of communication failure and maintains local flexibility to the most possible extent. Local public transport priority and any other controller-specific features are also maintained during communication failures.

MOTION's hierarchical approach can use all kinds of local controllers, with no or very moderate adaptations. The internal optimization models allow for the use of any kind of local controllers, including ramp metering devices. Local controllers can be included by using signal program selection without the need for adaptation or new interfaces. In this way a control over the network can be migrated from local controllers to MOTION in an efficient low-cost way.

The MOTION's hierarchical approach uses low-bandwidth communication channels. No high-speed, real-time communication system is necessary. The communication can be restricted to update rates of 5 min, which keeps costs low and allows for implementation even under disadvantageous infrastructure conditions or with wireless connections.

Detector Requirements

Figure A11 shows typical detector configurations that are used by MOTION. Any detection technology can be used; however, the best operations are achieved with traditional induction loops. MOTION uses information from the detectors to estimate state of the traffic in the network under its control. One of the performance measures that is widely used for the traffic state estimation is queue length at intersection approaches. However, German intersections traditionally use local detectors that are installed near the stop-lines. These locations are perfect neither for measuring input flows and queue lengths nor for calculating output flows. The main purpose of most detectors in Germany, which are 10 to 60 m upstream of the stop-line, is the application of vehicle actuation methods. To use the existing detectors to compute queue lengths a new cycle-based queue length estimation method was developed. This method allows for the estimation of queue lengths that are up to 5 to 10 times longer than the distance between detector and stop-line. Based on these estimated queue lengths, MOTION is able to compute consequent delays and travel times (Mueck 2008).

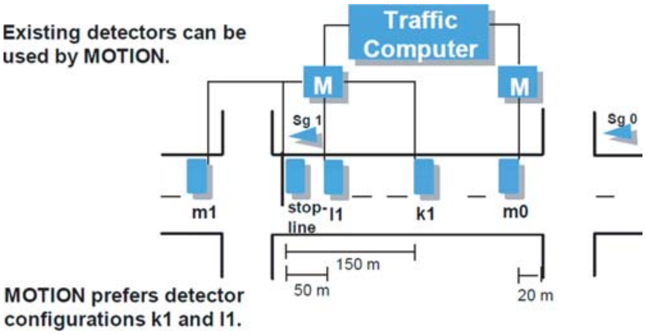


FIGURE A11 Detector placement in MOTION.

In real-world conditions, missing or faulty detector data are a phenomenon that cannot be avoided. If ATCSs' operations require second-by-second data, missing or faulty values can lead to a drastic reduction in the quality of the optimization, poor signal timings, and poor traffic performance on the streets. To avoid these problems, MOTION by its models only requires aggregated values and developers integrated an algorithm for the replacement of faulty or missing aggregated detector data. The algorithm provides substitution of the aggregated detector values when such values are not available from real detectors. The method guaranteed robust and reliable operations even with a significant proportion of faulty detectors. The method is not based on historic data patterns of the faulty detectors; however, it takes into account recent measurements of neighbouring detectors. The basic principle of this method is shown in Figure A11 (Mueck 2008).

For each of the detectors used by MOTION the measurements are collected in histograms showing the frequency of each measurement value relative to the frequency of all other values measured on the respective detector. In the case of a measurement failure the histograms of the failed detector and its neighbouring detectors are accumulated to sum curves, standardized by 100% (shown in the Figure A12). The recent flow values measured on the neighbouring detectors are reflected by their individual sum curves, producing specific percentage values (right side of the figure). The percentages lead to an average value, which is finally applied to the sum curve of the failing detector. The resulted flow value can be used as substitution for missing measurements. The method was tested on a network with 200 detectors and the results showed that the estimation error is less than 100 veh/hour in more than 90% of the estimated values.

Special Features

Public transport (PT) priority plays an important role in Germany. The dissemination of local PT priority has reached certain saturation levels in the German market. Because of the costly investments, the installed modern controllers and control designs cannot be simply replaced by shifting PT optimization to a network-wide level. There is concern that adaptive traffic control, which is operated at traffic control centers, could possibly jeopardize achieved quality standards of prioritization at local controllers (Mueck 2008).

Because priority for single PT vehicles cannot be provided by adjustments at a central level with its updating cycle of 5 to 15 min, MOTION has introduced a concept of automatically calculated frame signal plans. These frame signal plans are calculated individually for all controllers based on the results of network-wide optimization.

Frame signal plans include all parameters that are used to configure the local traffic-actuated operations and also all parameters that determine priority for locally detected PT vehicles. This concept provides MOTION with full flexibility to calculate cycle times, splits, stage sequences, and offsets and at the same time to preserve intended quality of PT priority at each controller in the traffic network. This method provides MOTION with the full capacity to coordinate traffic without restrictions imposed by PT priority settings at local controllers.

OPAC

The Optimized Policies for Adaptive Control (OPAC) strategy is a real-time signal timing optimization algorithm, which was originally developed at the University of Massachusetts, Lowell (Gartner et al. 2002). OPAC is a distributed control strategy featuring a dynamic optimization algorithm that calculates signal timings to minimize a performance function of total intersection delay and stops. The algorithm uses measured as well as modeled demand to determine phase durations that are constrained only by minimum and maximum green times and, if running in a coordinated mode, by a virtual cycle length and offset that are updated based on real-time data.

Originally, OPAC was developed as a distributed strategy featuring a dynamic optimization algorithm for traffic signal control without requiring a fixed cycle time. Signal timings are calculated to directly minimize performance measures, such as vehicle delays and stops, and are only constrained by minimum and maximum phase lengths. OPAC development progressed through four versions, which are briefly outlined here (Gartner et al. 2002).

- OPAC-1—Applied Dynamic Programming (DP) to solve the traffic control problem. Although this procedure ensures globally optimal solutions, it requires complete knowledge of arrivals over the entire control period, which makes it unsuitable for real-time implementation owing to the amount of processing involved as well as the lack of available real-time information.
- OPAC-2—Represented simplification of the OPAC-1 and it served as an intermediate phase for the development of a distributed on-line strategy. The control period was divided into stages, and each stage was divided into intervals. The program computed optimal switching times for the stages so that the overall delays to vehicles are minimized. Valid switching times are constrained by minimum and maximum phase durations.
- OPAC-3—Represented further simplification of OPAC-2, whose main problem was that it needed knowledge of arrivals over the entire stage length (1 to 2 min), which was difficult to obtain in practice. To use only readily available flow data without degrading the performance of the optimization procedure, a "rolling horizon" concept was introduced. The stage, which consists of n intervals, is called the Projection Horizon (or simply Horizon), because it is the period over which traffic patterns are projected and optimum phase change information is calculated. From detectors placed upstream of each approach actual arrival, data for k intervals can be obtained for the beginning, or head, portion of the horizon. For the remaining $n-k$ intervals, the tail of the horizon, flow data may be obtained from a model. A simple model consists of a moving average of all previous arrivals on the approach. An optimal switching policy is calculated for the whole horizon; however, only those changes that occur within the head portion are actually being implemented. Therefore, there is a chance for dynamically revising the decisions when more recent (i.e., more accurate) real-time data are obtained.
- OPAC-4—As part of FHWA's Real-Time Traffic-Adaptive Signal Control System (RT-TRACS) project, OPAC control logic was expanded to include a coordination (synchronization) strategy suitable for implementation in

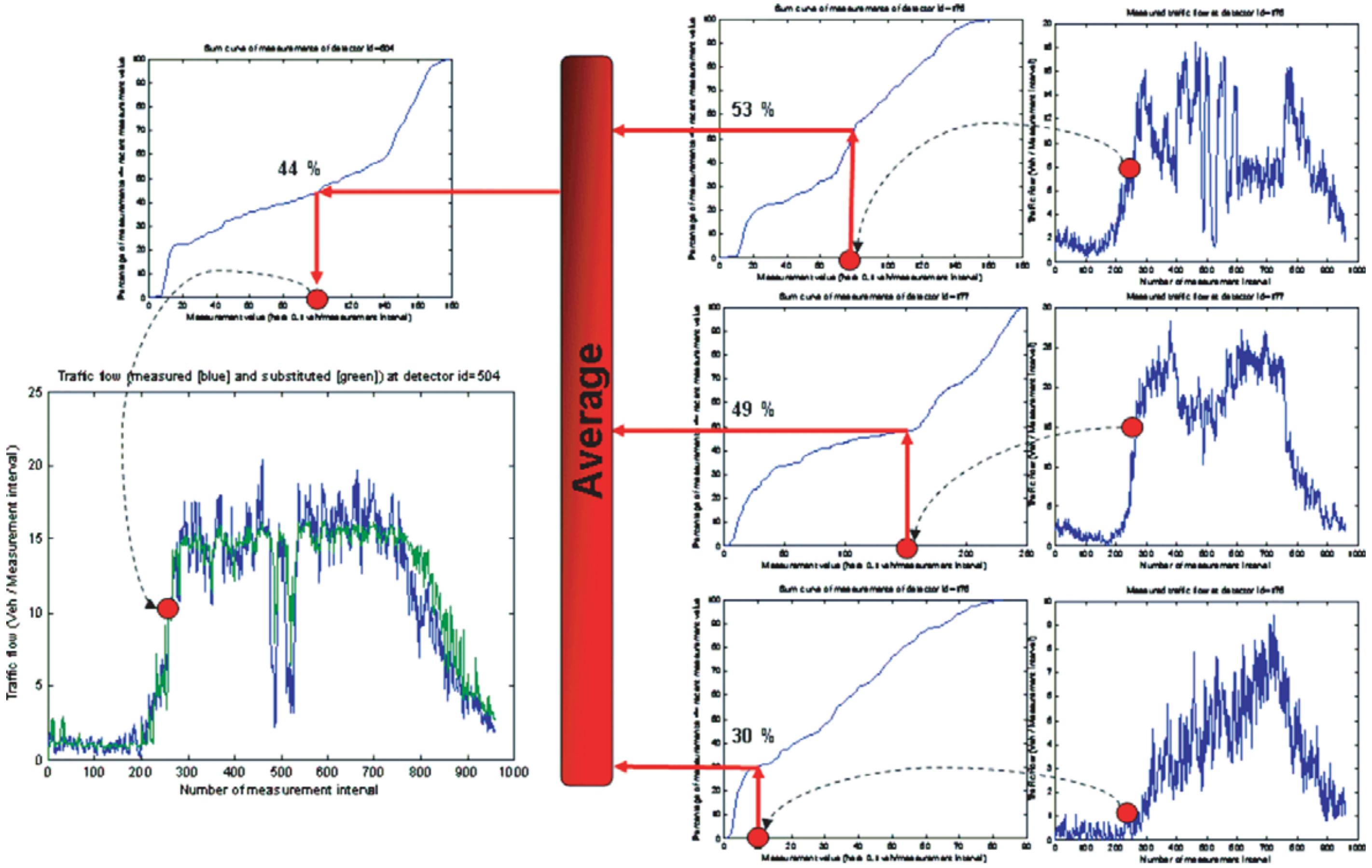


FIGURE A12 MOTION method of data substitute for faulty detectors.

arterials and networks. This version is referred to as Virtual-Fixed-Cycle OPAC (VFC-OPAC) because from cycle to cycle the yield point, or local cycle reference point, is allowed to range about the fixed yield points dictated by the virtual cycle length and the offset. This allows for the synchronization phases to terminate early or extend later to better manage dynamic traffic conditions. VFC-OPAC consists of a three-layer control architecture. Layer 1, the Local Control Layer, implements the OPAC rolling horizon procedure: it continuously calculates optimal switching sequences for the Projection Horizon, subject to the VFC constraint communicated from Layer 3. Layer 2, the Coordination Layer, optimizes the offsets at each intersection (once per cycle). Layer 3, the Synchronization Layer, calculates the network-wide virtual-fixed-cycle (once every few minutes: as specified by the user). The cycle length can be calculated separately for groups of intersections, as desired. Over time the flexible cycle length and offsets are updated as the system adapts to changing traffic conditions.

Adaptive Traffic Control Logic

VFC-OPAC allows, from cycle to cycle, the yield point or local cycle reference point to range about the fixed yield points dictated by the cycle length and offset. This allows the synchronization phases to terminate early or stay later to better manage dynamic traffic conditions. Over time, the cycle length and offset are also updated as the system adapts to changing traffic conditions. At the end of each cycle the OPAC logic determines whether to adjust the offset and what the upper and lower bounds are for the next yield point. The cycle length is calculated periodically by the central software, which can consider conditions at groups of intersections for which coordination is desired (e.g., an arterial). With these enhancements, the coordinated OPAC now provides a true adaptive control algorithm with many features including (Gartner et al. 2002):

- Full intersection simulation with platoon identification and modeling algorithm—Data from detectors upstream of the intersection are used to develop expected arrival patterns for all phases. The signal timing and these arrival patterns are used to estimate delay and stops. Depending on the veracity of the detector data, the patterns may be uniform, random, or in platoon.
- Split optimization for up to eight phases in a dual ring configuration—The phases whose splits are to be optimized is configurable. Minor phases, for example, can be left to the default control, whereas only major phases are optimized. Phases with no detectors can also be left out of the optimization because it would be based on unreliable estimates of demand.
- Configurable performance function of total intersection delay and/or stops—The performance function is a weighted function of total intersection delay and stops. The weights are configurable to eliminate delays or stops, or set their relative importance. Emphasizing delay causes OPAC to equalize delay among phases, which generally will lead to shorter cycles. Emphasizing stops causes OPAC to equalize stops among phases, which tends to mean longer cycles.
- Optional cycle length optimization—The central system optimizes the cycle length for each section or group of intersections. A "critical intersection" is determined periodically and the cycle length calculated based on data from the critical intersection. The goal of cycle length optimization is to meet phase switching timing determined by local conditions, while maintaining a capability for coordination with adjacent intersections. However, the algorithm uses a cycle length constraint, which means that the cycle length can start or terminate only within a prescribed range. As a result, all VFC-OPAC-controlled intersections can "oscillate" with a common frequency.
- Optional offset optimization is performed in the field computer using peer-to-peer data from adjacent intersections. Offset adjustments may be made as often as once per cycle. Options for offset adjustments are: leave the current offset (zero change), increase the offset for 2 s, or decrease the offset for 2 s.
- Free and explicit coordinated modes—OPAC may operate "free" where there are no cycle or offset constraints. Split optimization is constrained only by phase-specific minimum and maximum green. In "coordinated" mode split optimization is also constrained by dynamic cycle and offset values.
- Phase skipping in the absence of demand—OPAC may skip the user-selected phases when there are no demands
- Automatic response to changes in phase sequence—It is sometimes advantageous to have phase sequence change by TOD. For example, with lead/lag left turns, the leading phase can be changed between the morning and evening peak periods. OPAC automatically detects when these changes have been made and responds accordingly, although it does not itself determine or optimize phase sequence.

Hardware and Software Requirements

OPAC is designed to work with a variety of traffic signal controllers and firmware, including NEMA (TS-2), 170-ACT, 2070, and 2070-Lite controllers. With NEMA controllers OPAC uses Single Board Computers (SBC), whereas with ATC controllers OPAC uses a VME card (e.g., 68060). BI Tran systems software is used for 2070 signal controllers. At a central location OPAC requires multiple PCs for Operator Interface, a server, a database, device drivers, and a communication server (all shown in Figure A13). This configuration can usually control up to 250 intersections with no additional hardware upgrade. Usually OPAC comes integrated within MIST—an Advanced Transportation Management System developed and supported by Telvent Farradyne (Pooran 1998).

System Architecture and Communications

Figure A13 shows a typical OPAC system configuration with a two-level distributed system. The local level consists of Type 2070 controllers, which host the OPAC real-time adaptive control strategy. The adaptive strategy resides on a separate central processing unit card (68040) within the VME chassis of the controller. MIST provides the central system functionality, including operator interface, server, database, and communications between the central system and field controllers, as well as communications between adjacent controllers. Upstream loop detectors, installed on all through approach lanes to the intersection, are used to provide real-time traffic data (count and occupancy) to OPAC. For isolated intersection control OPAC architecture is fully distributed, whereas for coordinated intersections there are few tasks that are performed on a central level.

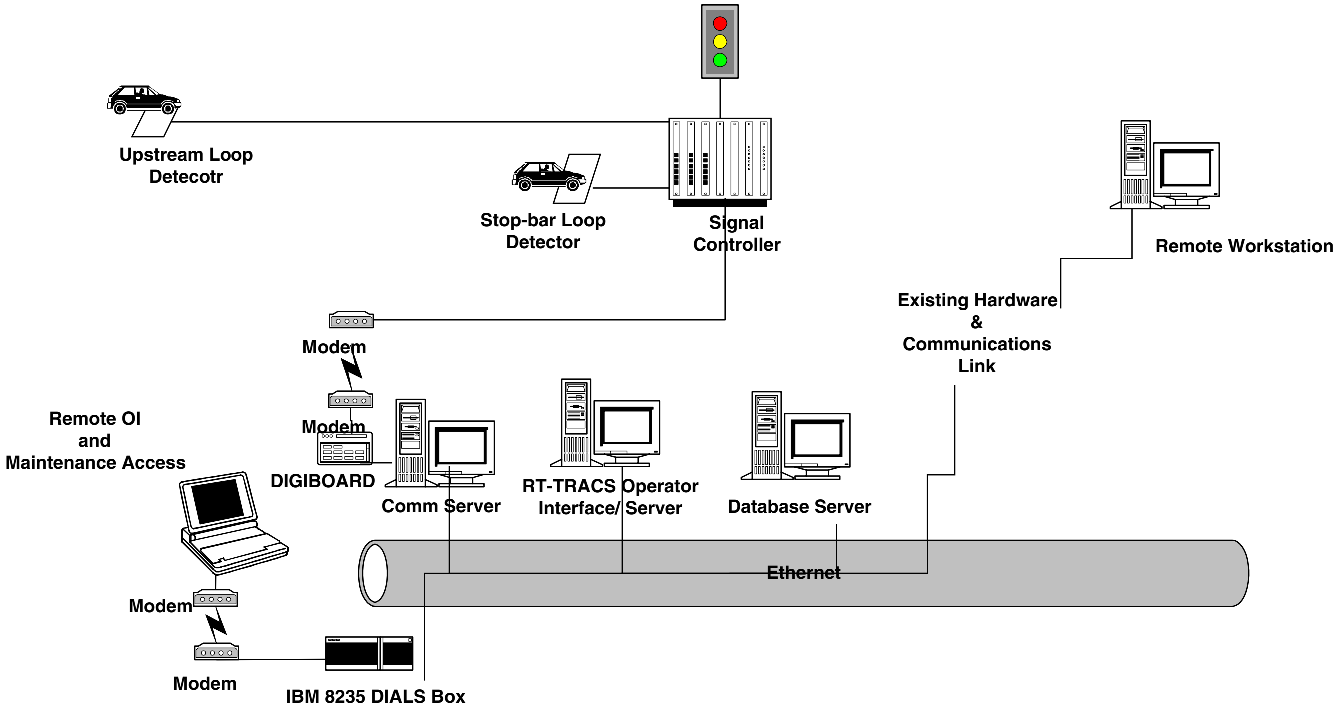


FIGURE A13 OPAC system architecture.

For example, cycle length is defined at central level and communicated periodically to the intersection controller. Also, if adjacent intersection controllers are not physically connected then peer-to-peer information is communicated through the central level (Pooran 1998).

For proper operations OPAC needs a dedicated central to field connection, at 9600 baud or higher. OPAC architecture can use phone lines, fiber optics, or wireless communication media, but the reliability of communication is crucial for the proper operations of the system. If communication between central level and local controllers fails OPAC will run autonomously. In this mode OPAC still runs its adaptive logic, but the coordination between intersections may be degraded. There are four communication levels within typical OPAC architecture. The following list provides the response rate for each of them (Pooran 2000):

- Central level—OPAC: OPAC status is polled once per 30 s.
- Central level—Controller firmware: once per second or once per 30 s.
- Controller firmware—OPAC: once per second.
- Peer-to-peer communications: once per 30 s.

Detector Requirements

OPAC can work with loop, radar, video, and any other detection technology that can provide the required data [volume, occupancy, and speed (measured or calculated)]. Ideal detector location is about 10 s upstream of the stop-line (at free flow speed) or upstream of the worst queue on each lane of all through phases. OPAC also requires one count detector in each lane of left-turn pockets as far upstream as possible.

Special Features

OPAC has special features to support traffic operations in oversaturated conditions. For isolated intersections, OPAC provides maximum green to the affected phase(s) if occupancy on the OPAC detectors exceeds a user-specified threshold. For coordinated intersection control, oversaturated conditions are handled through provision of maximum green to congested phases, subject to the current length, and adjustment of cycle length in response to increasing congestion.

RHODES

RHODES (Real-Time Hierarchical Optimized Distributed Effective System) is a real-time traffic adaptive signal control strategy that seeks to optimize the real-time performance of a corridor or network of intersections. To provide "optimal" control of traffic through a network, the system:

- Takes real-time input from vehicle detectors,
- Predicts the future traffic streams throughout the network, and
- Outputs "optimal" signal control settings based on these predictions.

The basic concept behind the RHODES strategy and algorithms is to set signal phasing that proactively responds to stochastic variations in traffic flow. This requires (1) the identification of various traffic objects at different levels of aggregation—individual vehicles, platoons of vehicles, and overall traffic flow in terms of vehicles per minute; (2) the identification of their natural dynamics and responsiveness to signal control; and (3) setting phase durations to allow these traffic objects to move according to their objective.

Perhaps the biggest difference between RHODES and "traditional" traffic control is that RHODES sets phase durations explicitly rather than timing parameters such as splits, cycle lengths, and offsets, as is done with traffic-responsive systems. This difference is what allows RHODES to "proactively respond" to the stochasticity of traffic, rather than forcing traffic to move in a cyclical fashion.

Adaptive Traffic Control Logic

Rather than reacting to changes in traffic conditions, RHODES uses peer-to-peer communications and predictive algorithms to identify upcoming changes and prepare accordingly. With RHODES, there is no explicit coordination; that is, there are no offsets and no fixed cycle lengths. The cycle length will vary from cycle to cycle, depending on current conditions and demand. Instead, the peer-to-peer communication and data exchange between intersections is able to provide "implicit" coordination that varies based on demand within the network.

Working in tandem with the signal controller, RHODES expands the controller's existing feature set by adding adaptive control capability. This allows for the use of RHODES on an as-needed basis; for example, during special events or as part of regular TOD operation during select periods. The RHODES system is comprised of two separate software modules, RHODES and PREDICT. RHODES is responsible for the real-time control of an intersection's traffic signal control. Using information provided by presence detectors at the stop-bar of each approach and passage detectors located upstream of each approach, RHODES determines the optimal phase sequence and green times that will minimize the delay incurred by vehicles passing through the intersection. The second module, PREDICT, provides estimates of departures that are heading toward neighboring, or peer, intersections, in effect extending the upstream detection capability of those intersections receiving information from PREDICT.

In this manner, information about vehicles' movements are passed from intersection to intersection, providing a method for *implicit* coordination of traffic signals along a corridor, as opposed to the explicit coordination imposed by traditional coordinated signal control.

Essentially, RHODES acts as a very intelligent high-level controller, similar to a coordinator, to monitor the operation of the traffic signal and adjust the phasing to meet a desired objective, typically a reduction in vehicle delay. By operating in this manner, the basic infrastructure of the signal control environment is unchanged, which serves to isolate RHODES from the rest of the cabinet, providing a measure of protection, while also insulating RHODES from the specifics of the hardware interface.

RHODES operates in two distinct modes, Standby and Online. In Standby, RHODES is in a "passive" mode, receiving and processing data from the traffic controller once each second. In Online, RHODES continues to receive and process data once each second, but is now "active" and performs the additional step of issuing holds, force-offs, and omits to the traffic controller to effect optimal phase timing. Typically, RHODES changes mode; for example, from Standby to Online or vice versa, in response to a request sent by the traffic controller, usually in conjunction with a plan change. In this way, RHODES can be configured to run as an alternative mode of operation during specific times by setting up an "Adaptive" plan within the controller, much as a Free or Coordinated plan would be used. In addition, RHODES may take itself out of Online mode, returning to Standby if there is a loss of data that would affect its ability to provide proper traffic control operation.

Note that even though RHODES appears to control the signal operation while in Online mode, the traffic controller is only acting as RHODES' proxy, placing the phase requests on its behalf. As a result, the safeguards in place within the controller and cabinet environment are still in force. This means that, should RHODES request an improper action; for example, terminating a phase before its minimum green time has been satisfied or serving conflicting phases, the request will be ignored, with the controller operating as expected; for example, continuing to serve the current phase until the minimum green has been satisfied. Therefore, all minimum green times, clearance intervals, and similar parameters programmed within the traffic controller will be honored at all times, regardless of the mode RHODES is in. If these parameters differ in value with those programmed into RHODES, the values in effect on the controller are those that will actually be used. Thus, data inconsistency between the two will only result in performance degradation rather than a potential safety issue. Even in the unlikely event that the RHODES system becomes unresponsive or fails, the controller will revert to its own traffic control method; for example, Coordinated or Free operation, so that proper traffic operation may continue.

Hardware Requirements and Configurations

Currently, the processing and memory requirements of RHODES are such that the native processors on existing traffic controllers are incapable of supporting its operation. As a result, a field-hardened single board computer is used as the hardware platform for RHODES. In addition to OS9, RHODES is also capable of running under both Windows and the Linux operating systems for added flexibility when considering how to integrate RHODES within an existing traffic control system. Currently, RHODES has operated under three different traffic controller hardware configurations.

1. *RHODES with 2070 Advanced Traffic Controller* (*ATC*)—The preferred RHODES configuration is one that uses the 2070 ATC as the controller platform, running the NextPhase software package. The 2070 ATC is used to interface with the cabinet hardware and supports a variety of cabinet environments through the use of different field input/output modules.
2. *RHODES with Econolite ASC/2S*—Although the 2070 ATC is becoming common in the transportation community, other controllers have been available for much longer and have well-established client bases. One of the most common is the Econolite ASC/2S series of controllers, which come in a variety of configurations to support different cabinet environments. To provide an option to the standard 2070 configuration, an "Adaptive" ASC/2S was initially developed that added an adaptive interface component to the base ASC/2S functionality. In this configuration, the ASC controller software was modified to incorporate communications with the AdaptEx interface module to provide support for RHODES. Later, these ASC controller

software changes were made part of the standard build, so that an off-the-shelf ASC/2S could be used, eliminating the need for the specially modified "Adaptive" ASC/2S and requiring only a serial cable connection with the external RHODES processor.

3. *RHODES with RHODES Adaptive Control Unit* (*RACU*)—Although RHODES is capable of communicating with traffic controllers by means of the Adapt and AdaptEx interface modules, not all traffic controller software is capable of running these interfaces. In addition, unlike with the ASC/2S, modifying the controller software may not be an option. Faced with these problems, a hardware solution was developed that allows RHODES to control a standard NEMA controller through the use of a RACU, which is essentially a stripped-down 2070 ATC. Although this is not the "preferred" hardware configuration for RHODES and is no longer in use, it demonstrates that RHODES may be interfaced with various types of traffic control hardware to realize an adaptive control system.

As discussed, RHODES does not interact directly with its environment, instead relying on the traffic controller and controller software to provide data about signal status, detector calls, etc. For this reason, RHODES is independent of the actual traffic cabinet environment. It has been deployed in TS1, TS2 Type 1 and Type 2, and 170-style cabinets and could also be deployed in an Intelligent Transportation System (ITS) cabinet environment. As long as the traffic controller software supports RHODES, the cabinet environment has no direct impact. Currently, RHODES support is only provided through two software products, Adapt and AdaptEx, both developed by Siemens ITS. Adapt is an adaptive control module that provides an interface between RHODES and the NextPhase traffic control software used on the 2070 ATC. AdaptEx provides similar functionality in an external module that interfaces with the ASC controller software.

System Architecture

Figure A14 shows a typical RHODES system architecture at each traffic signal intersection.

Communications

RHODES requires a communications network that is capable of providing reliable transmission of data between peer intersections on a second-by-second basis. RHODES relies on peer-to-peer communications; that is, data exchanged between adjacent intersections to make accurate predictions about future demand and therefore provide proactive, rather than reactive, traffic control. The component that provides this peer-to-peer data is the PREDICT module, which is responsible for calculating the number of vehicles that depart the local intersection en route to each peer intersection. Instead of a proprietary protocol, the IP is used, with each intersection assigned a set of unique IP addresses to identify it among its peers. To manage this communication, some networking configuration is required to support proper routing and identification between peers.

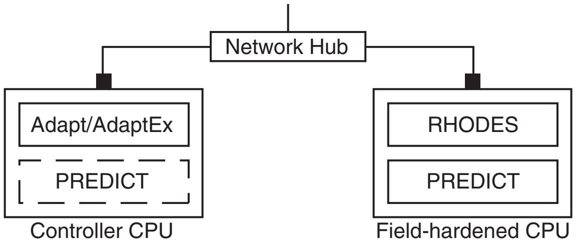


FIGURE A14 RHODES system architecture.

Detector Requirements

RHODES requires the installation of a number of detectors to properly model the flow of vehicles into and out of an intersection while it is in operation. Figure A15 shows the placement of detectors in a typical installation. "Stop-bar," or presence, detectors are required at each approach and are used to identify the presence (or absence) of queues. In RHODES, queues are associated with individual movements on an approach; that is, left, through, and right, rather than individual lanes, so multilane movements need only a single detector spanning these lanes. Typically, these loops are 6 ft wide and extend a distance of 20 to 70 ft from the stop-bar, depending on the type of detection system used and the agency's policy. Because these detectors are used by RHODES to identify the presence of a queue, the length would be large enough to prevent a queue from "dropping out" as it discharges, as this will be incorrectly interpreted as an empty queue.

Although presence detectors are associated with movements, upstream passage detectors, on the other hand, are used to provide counts of incoming vehicles and therefore need to be separated out by lane to ensure that vehicles are not missed. For this purpose, 6 ft × 6 ft loops, or their equivalent (e.g., in radar or image detection systems), are typically used. To provide accurate counts of incoming vehicles, it is important that these passage detectors be placed behind the farthest queue that typically forms to ensure that spillback over the detector does not take place. Mid-block placement is strongly recommended for this reason, but closer installation can be accommodated, albeit with a reduction in performance. Typically, these detectors are placed a minimum of 250 ft to 400 ft behind the stop-bar.

In addition to these baseline requirements, placement of additional detectors can improve the performance of RHODES and should be considered. Long-turn bays that experience a high volume at times are good candidates for additional passage detection near their entrances. These detectors will ensure that RHODES has an accurate count of the number of vehicles in the turn movement queue. Otherwise, RHODES relies on the current turn proportion parameters in use to decide how many incoming vehicles will be assigned to the turn movements, which can vary throughout the day. Note that this is for both left- and right-turn movements, as shown in Figure A15.

The PREDICT component of RHODES provides advanced notice of arriving vehicles to peer intersections and can also benefit from additional detection. In this case, placement of "far-side" passage detectors can be used to provide actual counts, rather than estimated counts, of departing vehicles heading toward a peer intersection. Locations with high volumes and highly variable turn proportions at the upstream peer intersections are good candidates for installation of far-side detectors because they are not affected by these fluctuations and will provide improved count accuracy for the downstream peer intersection.

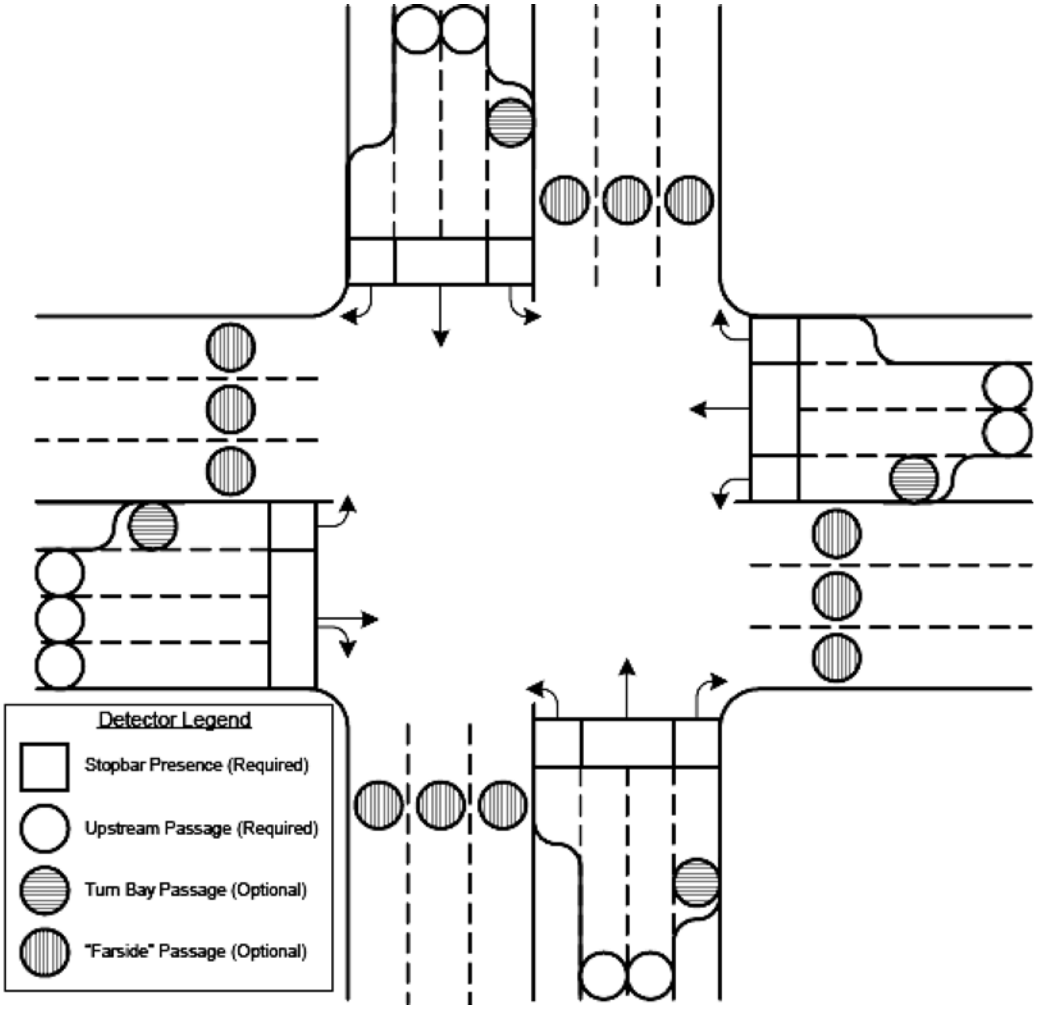


FIGURE A15 RHODES detection requirements.

The performance of RHODES is highly dependent on the accuracy and quality of the detection system, but is not dependent on a particular type of detection technology. Therefore, proper maintenance and monitoring of the detection system is a requirement for any RHODES installation. To this end, future revisions of RHODES will incorporate algorithms to recognize detector failures so that an alarm can be set for notification. In addition, the extent of the failure upon RHODES will be assessed so that the system can either continue operating or be taken off line, as appropriate.

SCATS

The Sydney Coordinated Adaptive Traffic System (SCATS) (current version 6.7) is an Area Traffic Control (ATC) or Urban Traffic Control (UTC) system consisting of hardware, software, and a unique traffic control philosophy that operates in real time; adjusting signal timings in response to variations in traffic demand and system capacity as they occur. Rather than changing individual intersections in isolation, SCATS manages groups of intersections that are called "subsystems," the basic unit of the system. Each subsystem will consist of a number of intersections, usually between one and ten. One of those intersections is designated as the controlling or "critical" intersection.

SCATS adapts and coordinates the intersections within each subsystem and is able to coordinate adjacent subsystems. This coordination aims to divide the traffic on major roads into "platoons" (groups of vehicles) and to allow just enough time for each platoon of vehicles to progress through the system while allowing the green time required for competing flows. This maximizes the network capacity for the benefit of all users.

Adaptive Traffic Control Logic

Strategic and Tactical Control

In SCATS traffic control is affected at two levels, *strategic* and *tactical.* Strategic control is managed by the regional computers and is known as the Masterlink mode of operation. Using flow and occupancy data collected at the intersection from loop detectors in the road pavement the computers determine, on an area basis, the optimum cycle time, phase splits, and offsets to suit the prevailing traffic conditions as they occur. The strategic and tactical control methods operate together to provide a powerful but flexible operation. Strategic control provides overall system control of cycle time, phase split, and offset. Tactical control provides significant local flexibility within the constraints of the strategic control parameters.

Tactical control is undertaken at the intersection by the local traffic signal controller (local controller) and meets the cyclic variation in demand. Tactical control primarily allows for green phases to be terminated early when the demand is low and for phases to be omitted entirely from the sequence if there is no demand. The local controller bases its tactical decisions on information from vehicle detector loops at the intersection, some of which may also be strategic detectors.

Masterlink

This is the real-time adaptive mode of operation. In Masterlink mode the regional computer determines the phase sequence, the maximum phase duration, and the duration of the pedestrian green signal displays. The local controller may terminate any phase under the control of the local vehicle actuation timers or skip phases without a demand, unless prohibited by instructions from the regional computer.

The regional computer controls the phase transition points in the local controller, but subject to the local controller safety interval times being satisfied (e.g., minimum green, intergreen, and pedestrian clearance). On completion of the transition to a new phase, the local controller times the minimum green and minimum pedestrian green intervals, and then waits for a phase termination command from the regional computer. On receipt of the command to move to the next phase, the local controller then independently times the necessary clearance intervals (e.g., intergreen) for the phase termination.

Subsystems The subsystem is the basic unit of SCATS strategic control. One subsystem is configured for each *critical* intersection, which are intersections that require accurate and variable phase splits owing to their operational characteristics. The intersections in a subsystem form a discrete group, which are always coordinated together. They share a common cycle time, with an inter-related phase split and offset. Phase splits for all other intersections in the subsystem are by definition non-critical, and are therefore either non-variable, or are allocated phase splits that are compatible with the splits in operation at the critical intersection. To provide coordination over larger groups of signals, subsystems can be configured to link with other subsystems to form larger systems, all operating on a common cycle time as determined by the links at the time. These links may be permanent or may link and unlink adaptively to suit the prevailing traffic patterns. A SCATS regional computer has a maximum of 250 subsystems.

Degree of Saturation SCATS strategic control bases its decisions on a measure of traffic demand known within SCATS as Degree of Saturation. In the SCATS context, Degree of Saturation is an empirical measure that is defined as the ratio of effectively used green time to the total available green time. Using loop detectors at the critical intersections, the local controller collects flow and occupancy data during the respective green phase. These data are sent to the regional computer, which calculates the DS. The DS is used as a basis for determining whether an increase or decrease in both cycle time and phase split is required.

Phase Sequencing The signal cycle is divided into phases, and up to seven primary phases are available. Each primary phase may additionally have several optional sub-phases, subject to certain criteria. The primary phases (A, B, C, etc.) can be introduced in any defined sequence. Any phase can be skipped if there is no demand for that phase. The sub-phases have no direct SCATS specification or control; however, they are normally labeled with a numerical suffix (e.g., B1, B2). The sub-phases effectively extend the flexibility of signal control within the bounds of the primary phase (e.g., left overlap phases).

Cycle Time Cycle time is increased or decreased to maintain the DS at a user-definable value (90% is typical) on the lane with the highest value. Cycle time can range between 20 s and 240 s and the actual lower and upper limits used are configurable on a subsystem basis. Cycle time can vary by up to 21 s per cycle; however, this upper limit is resisted unless a strong trend is recognized.

Phase Split Phase splits are specified as a percentage of the cycle time or as a fixed time in seconds. For critical intersections, phase splits in percentage are varied by a small amount for each cycle in such a way as to maintain equal DS on competing approaches. The minimum split that can be allocated to a phase can be configured, but is limited by a value determined from the local controller's minimum phase length. The current cycle time and the minimum requirements of the other phases limit the maximum split that can be allocated to a particular phase.

Offset A number of offsets are configured for each intersection within each subsystem and also between the subsystems that can link together. Offsets are selected on the basis of traffic flow for each subsystem. The higher traffic flow links select the offsets that provide good progression for that link. Optimal offsets on the higher flow links tend to minimize the total number of stops in the system, reducing fuel consumption and increasing the capacity of the network overall.

Other SCATS Operating Modes

Besides the real-time adaptive traffic control mode (Masterlink), SCATS can run a variety of other "auxiliary" traffic control modes. Table A1 identifies these modes accompanied by short descriptions.

Other important SCATS features are:

- Hurry Call—the local controller invokes a pre-programmed mode usually associated with an emergency phase or local pre-emption such as a railway-level crossing phase.
- Schedule—SCATS allows for system operation to be scheduled. Scheduling can operate with any mode of SCATS operation and can be used to switch between modes. Almost any function that can be executed manually can also be configured to occur at specified times on specified days.
- Special Routines—a range of special routines is available in SCATS, which allows the user to vary operations to suit special conditions. Special Routines generally provide an extension to the default adaptive behavior of the Masterlink mode. It is features of this type that enable every detail of signal operation to be tailored to meet the operational needs of each individual intersection.

Hardware and Software Requirements

The SCATS regional traffic control software has a maximum capacity of 250 intersections per region. With a maximum of 64 regions, the total capacity is 16,000 intersections.

TABLE A1
NONADAPTIVE SCATS OPERATING MODES

Operating Mode	Description
Flexilink	Intersections are synchronized by local controllers clock and are therefore coordinated without any connection. Signal timings and phasing sequence (stored at the local controller) are determined according to a time of day schedule. Local tactical control is still operational in this mode, unless prohibited by instruction from Flexilink.
Police Off	The lamp state at the local controller has been turned off.
Police Red	All lamps at the intersection have been turned to red.
Police Manual	The phases at the local controller are being manually introduced.
Maintenance Mode	This mode provides an indication to an operator that a technician is on site servicing the controller.
Flashing Yellow	The normal signal display is replaced by flashing yellow displays on all approaches, or flashing yellow and flashing red to competing approaches.

Regional Computers

The regional traffic control function uses standard PCs operating under the Microsoft Windows® operating system. A range of intersection communication methods is provided and includes network (TCP/IP), serial, dial-out, and dial-in.

Central Management Computer

The Central Management Computer is a PC operating under the Microsoft Windows® operating system. Communications with regional computers and workstations is through TCP/IP.

Software

SCATS comes with the Central Management Computer software that allows other software packages including SCATS support software to be used as part of the traffic management package. All SCATS software modules (i.e., regional, central, picture developer, alarming and monitoring, and simulation) use a PC platform and are compatible with the Microsoft Windows© operating system. SCATS provides the end user with a modern GUI with a full capability in monitoring and controlling SCATS and traffic signal functions.

System Architecture and Communications

Architecture

SCATS has been designed in a modular configuration to suit the varying needs of small, medium, and large cities. In its simplest form, a single regional computer can control up to 250 intersections. Expansion of the system is achieved by installing additional regional computers on a TCP/IP network. SCATS also has the ability to internally manage several instances of the regional traffic control software on one physical computer. This provides flexibility in hardware configuration and for simulation use. All systems have a Central Management Computer to manage global data, access control, graphics data, and data backup. A typical SCATS system is shown in Figure A16.

Communications

SCATS 6 supports the following communication methods between a region and an intersection:

- Serial—for example, dedicated cable, leased line.
- Network (TCP/IP)—for example, dial IP or ADSL using TCP/IP.

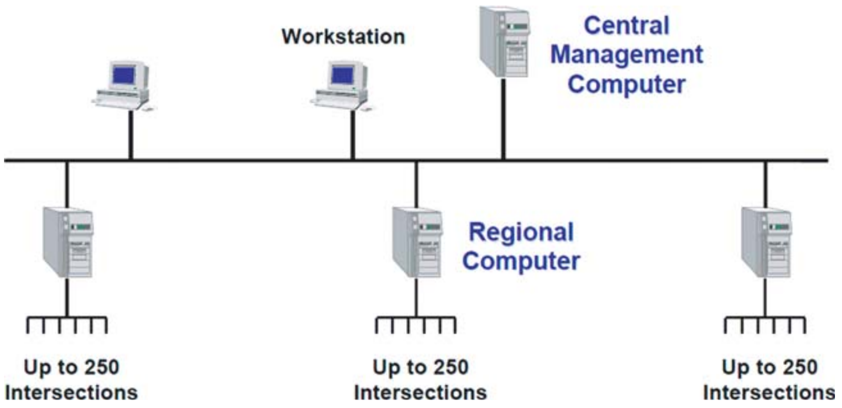


FIGURE A16 Typical SCATS system architecture.

- Dial-out—using the SCATS DIDO unit.
- Dial-in—using the SCATS DIDO unit.

There are messages to and from each intersection controller every second. The minimum requirement is 300 bits per second (baud). The low speed rate required for SCATS communications allows for a high degree of tolerance in the reliability of the communications network.

In the event of regional computer failure, loss of communications between the computer and any local controller, failure of all strategic detectors, or certain other local malfunctions, the affected intersections will revert to a user-defined fallback mode of operation. This may be either Flexilink (the usual fallback mode) or Isolated mode.

If specified by the user, fallback at one intersection will also cause other intersections in the subsystem to operate their fallback mode and, optionally, intersections in adjacent linked subsystems. In this way, if Flexilink is specified as the fallback mode, a significant degree of coordination can be maintained between intersections affected by the failure during the period of fallback.

Detection Requirements

Tactical Detectors

Tactical detectors are located at the stop-line to enable differentiation between the left-turn, straight-through (ahead), and right-turn movements at the intersection, both by knowledge of the lane usage in lanes of exclusive use, and by speed differential in a lane shared by two or more movements. Tactical detectors could be provided on all lanes of an approach (or movement) that would benefit from tactical control. At a minimum, tactical detectors could be provided for minor movements.

Strategic Detectors

Strategic detectors measure how effectively the green time is used by traffic that is controlled by SCATS. Correspondingly, SCATS uses strategic detectors to accurately determine the required green time for an intersection approach. Stop-line detectors installed for tactical control are used as strategic detectors, subject to certain criteria. Strategic detectors can be also located upstream from the stop-line, in which case the calculation of DS will be biased and detection of traffic queues becomes possible. At times, stop-line detectors at the upstream intersection are used to control a downstream intersection (it helps to identify queues). It is logical that approaches most requiring strategic detection are those least requiring tactical detection, and vice-versa. However, the installation of detectors at all intersection stop-lines regardless of fundamental need provides a degree of redundancy and increased strategic control flexibility.

The length of strategic detectors is critical for accurate calculation of DS. Detectors shorter than a critical length tend to perceive traffic as widely spaced in the conditions of slow moving, closely spaced traffic. Conversely, if the detectors are too long they would not measure any spaces when traffic moves freely. Historical research has shown that a suitable detector length is 4.5 m, but acceptable lengths go as low as 3.5 m. All detectors (i.e., including tactical detectors) might be provided at a length suitable for strategic detectors so that strategic detectors can be selected from any of the detectors provided at any time.

Special Features

Route Preemption

Route preemption allows a user to manage the sequential introduction of a green window or green wave through several intersections and is typically used for emergency vehicles or convoys.

Time/Distance Display

Figure A17 shows a time distance diagram for viewing signal coordination in real time. The relationship of coordinated phases and offsets is displayed dynamically in real time.

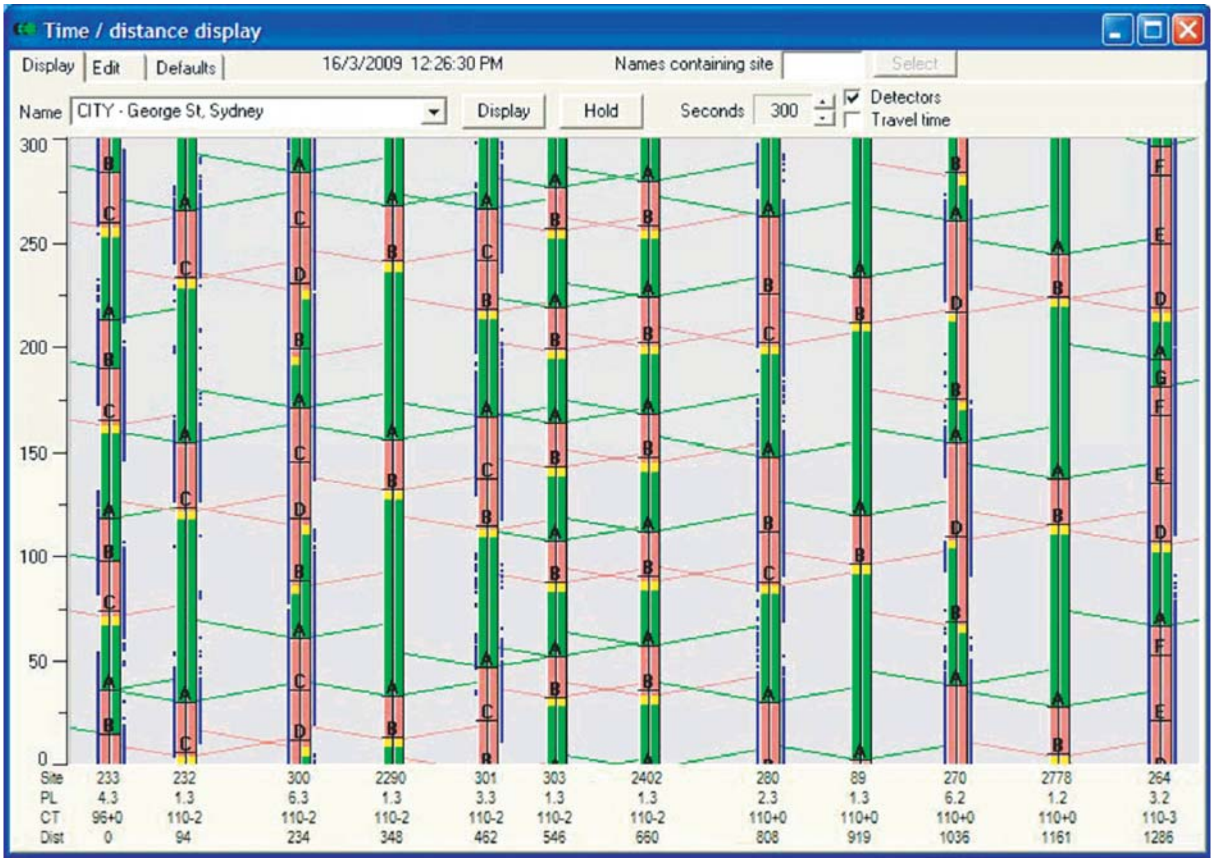
SCOOT

Adaptive Traffic Control Logic

In SCOOT optimization of traffic control in the network is achieved using small, regular changes in signal timings designed to avoid major disturbance of traffic flow. Loop detectors are polled by the controller for occupancy every one-quarter second and typically transmitted once per second to the central computer, although the latest version of SCOOT relaxes this requirement. Detector data are processed at central in 1-s intervals. SCOOT uses a hybrid measure of volume and occupancy [also known as Link Profile Units (LPUs)] to express traffic demand at detectors. Approximately 17 LPUs equal 1 vehicle, although this value is variable depending on traffic behavior. The LPUs are then processed through a platoon-dispersion model, similar to the one used by TRANSYT, to create Cyclic Flow Profiles (CFPs). Using CFPs together with the red/green signal status, SCOOT is able to model a traffic demand profile at the stop-line (the queue on the approach). SCOOT's internal traffic model maintains a detailed, real-time image of the traffic network (similar to TRANSYT-7F or CORSIM). As such, a major part of a SCOOT system installation involves calibrating and validating the network model to match network field conditions. Overview of SCOOT operations is shown in Figure A18.

SCOOT has three optimization procedures by which it adjusts signal timings—the Split Optimizer, the Offset Optimizer, and the Cycle Optimizer. Each optimizer estimates the effect of a small incremental change in signal timings on the overall performance of the region's traffic signal network, which is measured through a performance index, a composite measure based on vehicle delays, and stops on each link. Calculated signal timings are transmitted to the local controller every second.

The Split Optimizer works at every phase change by analyzing the current split timings to determine whether the split time is to be advanced, retarded, or remain the same to achieve the degree of saturation. Split changes are typically in increments of ±1 or 4 s by default, but include the ability for operator-configured values to be used.



16/3/2009 12:26:30 PM

Name CITY - George St, Sydney

Seconds 300

☑ Detectors
☐ Travel time

Site	233	232	300	2290	301	303	2402	280	89	270	2778	264
PL	4.3	1.3	6.3	1.3	3.3	1.3	1.3	2.3	1.3	6.2	1.2	3.2
CT	96+0	110-2	110-2	110-2	110-2	110-2	110-2	110+0	110+0	110+0	110+0	110-3
Dist	0	94	234	348	462	546	660	808	919	1036	1161	1286

FIGURE A17 Time/distance display in SCATS.

The Offset Optimizer works once per cycle for each intersection. It operates by analyzing the current situation at each intersection using the CFP predicted for each of the links with upstream or downstream intersections. It then assesses whether the existing offset time is to be advanced, retarded, or remain the same. Offset changes are also in ±4-s intervals.

The Cycle Optimization operates on a region basis once every 5 min, or every two and one-half minutes when cycle times are rapidly changing. It identifies the "critical intersection" within the region (any of the intersections in a system or sub-area can determine the system cycle length), and will attempt to adjust the cycle time to maintain this intersection with 90% link saturation

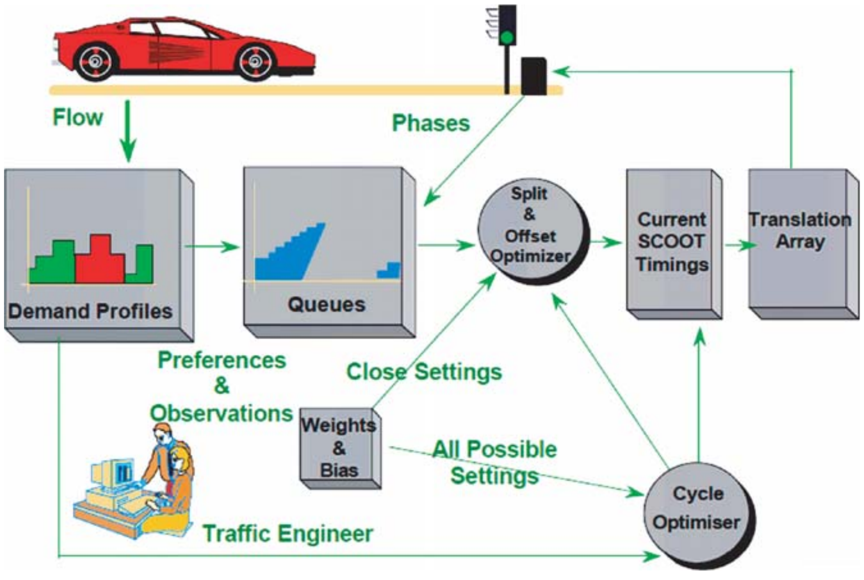


FIGURE A18 Overview of SCOOT operations.

on each phase. If it calculates that a change in cycle time is required, it can increase or decrease the cycle time in 4-, 8-, or 16-s increments depending on the current cycle time value. SCOOT is not constrained by a "master" intersection in determining system cycle lengths.

Hardware and Software Requirements

Standard Controller Firmware

SCOOT runs with standard Siemens SEPAC firmware, the same firmware used for standard intersection control at 50,000 intersections across the United States. Older SCOOT systems used an EPAC controller firmware upgrade for the existing controllers. SCOOT can also be installed with pre-programmed logic on new EPAC and 2070 controllers.

SCOOT Software Platforms

The kernel software at the heart of a SCOOT system is standard for all installations. The additional software that links the SCOOT kernel to on-street equipment and that also provides the user interface is supplier-specific.

Traditionally, SCOOT kernel has been operating on Alpha DEC computers and Open VMS operating system. Recent versions of SCOOT also operate on a PC platform with a Microsoft Windows operating system. The PC platform provides the following benefits:

- Use of standard PC components,
- Reduced hardware and software costs,
- Improved network efficiency,
- Ease of use and training for new users,
- A customized congestion management tool kit, and
- Improved access to data management.

System Architecture and Communications

Figure A19 shows a typical SCOOT architecture. A SCOOT system can implement a centralized strategic traffic policy, reacting to variations in demand in real time. The centralized system also allows system-wide strategies to be employed. Examples of these strategies are:

- Peak hour routes,
- Keeping emergency and evacuation routes clear,
- Traffic metering (gating) on the outskirts of congested areas, and
- Central bus priority.

Traditionally, SCOOT has been using dedicated (leased line, copper cable, fiber optic, or combinations) multi-drop transmission lines to outstations. SCOOT requires second-by-second communications between the central computer and outstations. Typically, six to eight intersections can be served by 1200 baud rate. Recently, the PC version of SCOOT was enhanced to enable the use of modern communications technology used by ITS solutions. This approach absorbs inconsistencies and delays in data delivery with less impact on the system. This new approach reduces dependency on traditional leased-line communications techniques and opens up the potential to use a wide range of modern communications technologies previously unavailable to SCOOT systems.

Detection Requirements

SCOOT uses upstream detection to collect its traffic information. Upstream detectors are usually installed in the vicinity of the pre-

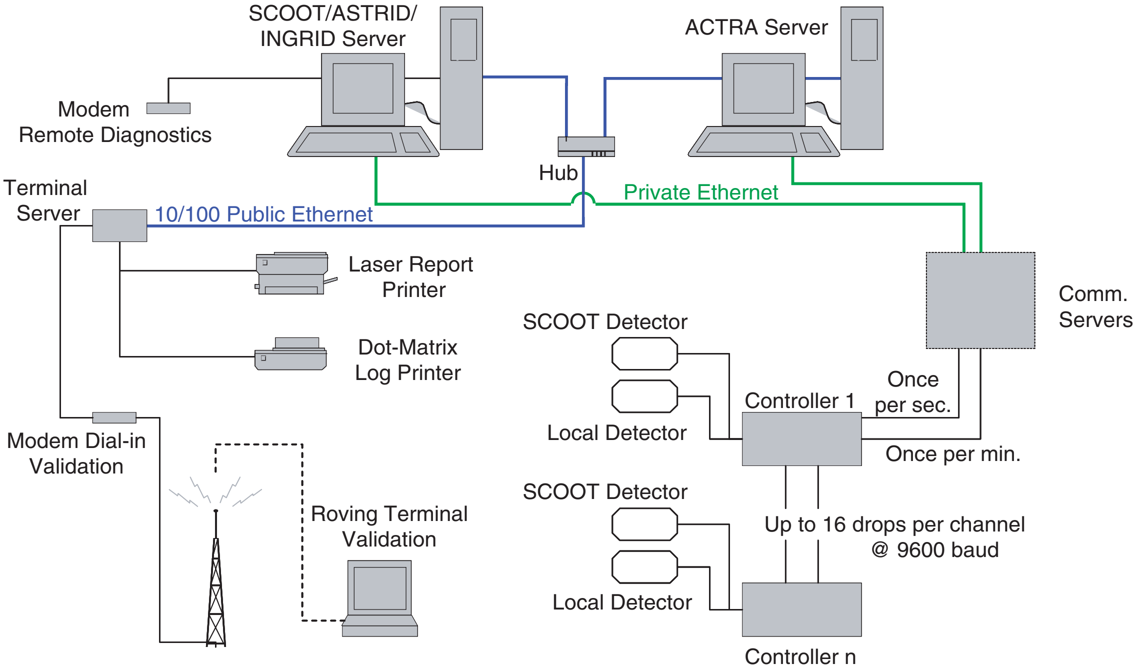


FIGURE A19 Typical SCOOT architecture.

vious upstream intersection to reduce communication costs. Ideally, SCOOT detection needs to be located at least 7 s of travel time upstream (further is acceptable and often better). Upstream detection provides a view of the traffic approaching an intersection in a TRANSYT type "flow profile." Utilization of the upstream detectors allows SCOOT to:

- Be more sensitive to sudden changes in traffic conditions,
- Be able to respond more quickly in congested conditions,
- Calculate queue lengths more accurately, and
- Base its changes on incoming "traffic flows," rather than latent "traffic demand."

Special Features

ASTRID and INGRID

Data used by the SCOOT model in the optimization process such as stops, delays, flows, and congestion levels, are available to the user through the ASTRID (Automatic SCOOT Traffic Information Database) system, which automatically collects, stores, and processes traffic information for display and analysis. When a detector fails and link data cannot be collected in real time, historical link data from ASTRID can be used by the SCOOT optimizers to maintain a high level of system efficiency.

The INGRID (INteGRated Incident Detection) system was developed to automatically detect traffic incidents in urban areas. The system uses information from SCOOT and the ASTRID database to compare current conditions with historic values. Information provided by INGRID includes time of incident, duration, location, area affected, severity, and confidence level.

Bus Priority

Two approaches to bus priority are available with the SCOOT system:

- Local-based priority, and
- SCOOT-based priority (only for intersections under SCOOT).

Local Priority Siemens ITS controllers provide up to six preemption (high-level) and six priority (low-level) routines. When the local equipment (the most common system is 3M's Opticom™) detects an approaching bus, it sends a request to the local controller to initiate the appropriate priority routine. This routine determines the current signal phasing, evaluates the direction of travel and whether the priority is for the main street or the minor street, and executes the preprogrammed response.

SCOOT-Based Priority SCOOT is able to specially accommodate buses within its normal optimization routines. Bus priority may be provided by green extensions, stage recalls, or both. An extension is given when a detected bus could be served by an extension of the current green. A recall is implemented when a detected bus is expected to arrive at the stop-line at a red light (i.e., the signal is currently red or a maximum length extension would not be sufficient to serve the bus in the current stage). In this case, the intersection cycles as quickly as possible to return to the bus stage.

It can be noted that there is no guarantee of priority to buses at an intersection. With each split decision, SCOOT will still take into account the percent saturation of all approaches, and will still maintain the principle of small but frequent changes. The detection of a bus merely gives a higher priority to that stage. This is in contrast to a full over-riding priority system that is constrained only by maximum and minimum stage lengths. Buses may be detected by either static means (e.g., loop detectors or 3M Opticom) or by means of an automatic vehicle location system.

Over-Saturated Conditions

SCOOT has several methods with which to handle over-saturated conditions:

- Congestion importance factors/congestion offset per link,
- Congestion links with congestion importance factors,
- Gating, and
- Variable-Intersection Based Target Saturation for cycle time optimization.

A congestion importance factor is specified for each link. It is used to influence split calculations in favor of the link when congestion is detected. Another factor, congestion offset, is a fixed offset, specified by the traffic engineer, to be used in congested conditions. Congestion weighting factor allows the engineer to specify the importance of achieving the congestion offset.

Gating, or action at a distance, allows the restriction of the green times of the entry links to the congested area; or, exiting links downstream of a congested area may be granted more green time to allow traffic to clear.

A cycle optimizer normally uses 90% as its target saturation level (80% when the "Trend Flag" is set, to give more rapid response). Intersection-based target saturation levels may be set by the traffic engineer, whereby a low threshold value will produce an early increase in cycle time and a high threshold value will allow an early drop in cycle time at the end of peak period.

UTOPIA

MIZAR's Traffic Light Control and Priority System, UTOPIA, was developed during the 1980s in response to the need for a fully automated system able to increase the fluidity of traffic and transport, and to reduce travel times across a wide-area network. UTOPIA is installed and operates in numerous cities throughout Europe.

The basic principle of UTOPIA is to perform a real-time optimization of the signal timings to minimize the total socioeconomic cost of the traffic system. These costs are usually expressed as traffic congestion, vehicular emissions, and travel times both for private traffic and for public transit vehicles. Control strategies are computed in real-time taking into account the measured traffic metrics at intersections as well as forecasted private traffic demand at both the intersection and network levels, and the predicted arrival times of the public transit vehicles at the intersections.

UTOPIA offers a full suite of traffic control strategies including:

- Fully Adaptive
- Time Based Plan Selection
- Traffic Actuated Plan Selection
- Traffic Responsive (micro-regulation).

These various strategies can be applied simultaneously at different zones within the same network. They can also be modified independently at any time of the day.

Fully Adaptive Control

The highest performance of UTOPIA traffic control is achieved in the fully adaptive mode in which UTOPIA responds in real time to traffic conditions on the network. The system calculates the control strategy using information sent every second from sensors located near each intersection.

Traffic control is determined through optimization processes and by the application of the rolling horizon technique at both the central and local levels:

- At the central level, the network control strategy is optimized over the next 30 to 60 min time horizon (depending on the size of the network controlled) and is updated every 5 min. Each strategy is effective for not more than 5 min, and is then replaced by a new strategy.
- At the intersection level, signal timing optimization is performed on the time horizon of the next 120 s and is repeated every 3 s. The resulting optimal signal settings are actually in operation only for 3 s.

Objective function, which is optimized at the intersection level, consists of terms related to the traffic observed on approaching links to the intersection and also those links to which can be applied one of the following two fundamental interaction principles:

1. A **strong interaction** principle that accounts for the delay at the downstream intersections experienced by vehicles leaving the intersection under consideration; or
2. A **look-ahead** principle that accounts for the traffic forecast during the entire optimization horizon (120 s) for all incoming links.

Implementation of the strong interaction principle requires knowledge of the traffic light status at the downstream intersections. On the other hand, implementation of the look-ahead principle requires knowledge of the traffic light status for the upstream intersections and the availability of traffic information for the incoming links of the upstream intersections.

To achieve stability and robustness at the network level, interactions are defined between the local level and the central level. At the central level, the optimal network traffic control problem is developed based on the macroscopic traffic model of the network, and control strategies such as minimum, average, and maximum length of each stage, offsets, and weights for all the elements constituting the objective function optimized locally are defined for each intersection.

The cost elements of the objective function optimized at the local level are:

- Travel time of the vehicles on the incoming links,
- Number of stopped vehicles on the incoming links,
- Excess queuing on the incoming links (queues that exceed thresholds proportional to the link capacity),
- Travel time of the vehicles on the outgoing links, and
- Travel time of public transit vehicles.

Cost elements are evaluated during the entire horizon taking into account existing signal timings and phasing constraints (e.g., minimum and maximum green times). UTOPIA allows for utilization of various weights for various links and priority rules. Figure A20 describes interaction between UTOPIA's two fundamental modules operational at both the local and central levels: the State Observer and the Controller.

The distributed architecture of the system derives directly from the method adopted to decompose the area optimal control problem into a set of simpler and strongly interrelated subproblems. Problem decomposition is performed following a topological rule: first, the area is subdivided into overlapping zones, where each zone is logically centered on an intersection and includes neighboring intersections as well. Then an optimal control problem is defined for each zone, which takes into account traffic data and traffic light control information related to the all the intersections within the zone. The solution of the zone control problem determines the traffic light control to be actuated at the central intersection only but, owing to the overlap between neighboring zones, is strongly interrelated with the control at all surrounding intersections.

Zone-by-zone control optimization is iterated frequently based on a rolling horizon technique to detect demand variations promptly and to react consequently. Because of the strong interaction, the effects of any demand variation in one zone are rapidly propagated to all the surrounding zones. This scheme allows UTOPIA to implement a fully adaptive optimal area control. Also, the control scheme supports the physical organization of the system according to a hierarchical and decentralized architecture, where the SPOT roadside unit performs the zone control functions at the intersection, whereas the central level determines dynamically the criteria and the reference strategies that need to be considered during local optimization.

Hardware and Software Requirements

Fully compatible with 32-bit and 64-bit architecture, the UTOPIA server(s) provides high performance with minimal require-

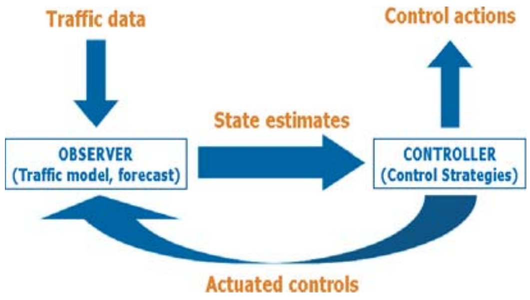


FIGURE A20 Interaction between modules in UTOPIA.

TABLE A2
REQUIREMENTS FOR UTOPIA SERVERS

Servers	Applications
Operating system	Microsoft Windows Server 2003
Database engine	Microsoft SQL server 2000/2005
Web Server	Microsoft Internet Information Services (IIS)
Map Server	Autodesk MapGuide
Application framework	Visual C++ Microsoft .NET Framework 2.0

ments. Typical requirements for UTOPA servers are provided in Table A2.

Requirements for Utopia Servers

UTOPIA uses Browser Based Clients to provide high accessibility to the system without requiring any specific workstation configuration. Although essentially independent of the Operating System, the UTOPIA web-based interface works best in common web browsers such as Internet Explorer 7 and Firefox 2. UTOPIA's interface offers full multi-tasking capabilities and different privileges can be provided for users of different administrative levels.

UTOPIA can be interfaced with the new OMNIA platform to facilitate monitoring of the traffic network and ATCS operations. Almost all of the UTOPIA's user interface functionalities are directly accessible from the OMNIA Common GUI. Specialized clients of the UTOPIA system need a specialized UTOPIA workstation (the MS Windows XP operating system is recommended).

System Architecture

UTOPIA has a two-level hierarchical and distributed architecture, which is shown in Figure A21. The higher level is responsible for setting the network control strategies, whereas the lower level (SPOT—at local intersection controllers) implements signal timings according to the actual local traffic conditions constrained by the network control strategy from the higher level. UTOPIA's architecture is modular, which makes UTOPIA a system easy to extend and integrate with other ITS applications (e.g., public transport management). The distributed architecture of the system derives directly from the method adopted to decompose the area optimal control problem into a set of simpler and strongly interrelated sub-problems.

SPOT

SPOT is the software that performs local UTOPIA functions in the intersection controller's cabinets. SPOT is installed as a separate unit that communicates with intersection controllers. SPOT also exchanges information with:

- Neighboring SPOT units to cooperate in the definition of the local control strategy and to implement dynamic coordination suitable for both private traffic and transit priority.
- Central system to receive commands, priority requests, and traffic control strategies, and to send traffic parameters, a locally actuated traffic control strategy, and diagnostic information to the central system.

UTOPIA Central Functions

The UTOPIA central functionalities can be assigned to three major groups, as shown in Figure A22. In the Traffic Network Monitoring group (far right) traffic measures (volumes, speed, classification data, etc.) and parameters (clearance capacities, turning proportions, actuated signal plans, etc.) are gathered and stored in the central system archive together with their statistical profiles. Automatic incident detection and congestion warning

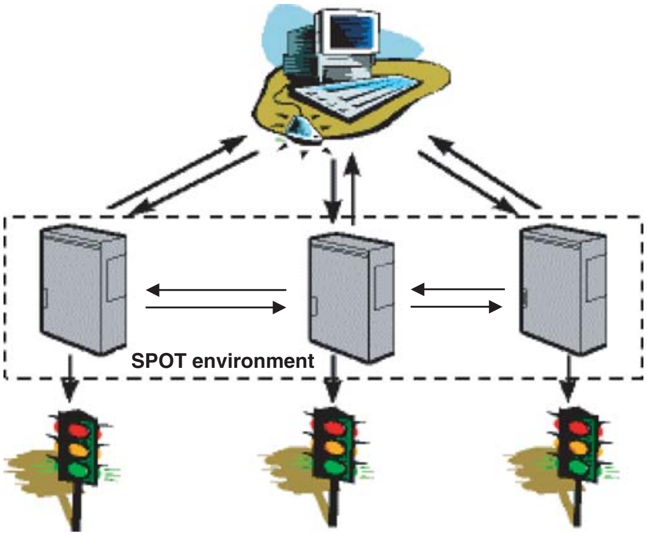


FIGURE A21 UTOPIA and SPOT interaction.

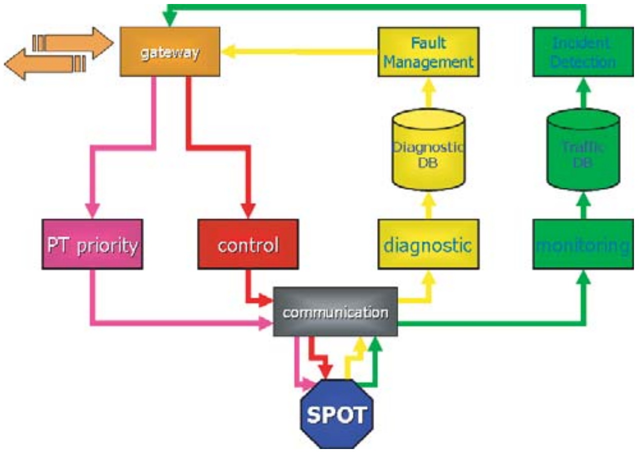


FIGURE A22 Functional architecture of UTOPIA.

functions feed further DB files. All data are made available for on-line, off-line, and export system processes. In the System Diagnostics group (second from right) information on the operational status is collected for all system components and made available to the operator through screen displays and special reports for monitoring and maintenance purposes. Automatic alarms are generated for abnormal situations. Finally, in the Traffic Control and Priority group (left) traffic control strategies are developed and delivered for implementation to the intersection level. Transit signal priority is handled in two ways: priority requests can be generated internally through the PT Locator functionality or received from an external fleet management system. In both cases arrival times of the priority vehicles are forecasted and forwarded to the intersections. Also, a backup priority management function is implemented at the local level based on the continuous exchange of information between the SPOT units. Traffic data and control strategies are also exchanged with other mobility management systems through a gateway to allow for cooperative monitoring and control of the area.

Detector Requirements

When UTOPIA runs fully adaptive control strategies, the traffic state estimation requires traffic detectors located on entry and exit lanes of the intersection approaches (shown in Figure A23):

- Entry detectors are needed to measure incoming traffic platoons and model expected queues at stop-lines, and
- Exit detectors are used to dynamically estimate parameters such as turning proportions and saturation flow rates.

UTOPIA requires detectors only on the intersection approaches with significant traffic volumes and where traffic fluctuates significantly. One can note that in an urban grid environment exit detectors from upstream intersections can serve as entry detectors for the downstream intersections. UTOPIA usually uses queue detectors at the approaches where queues typically are critical. Any detection technology can be used providing that it reports two fundamental detection measures: traffic counts and occupancy time.

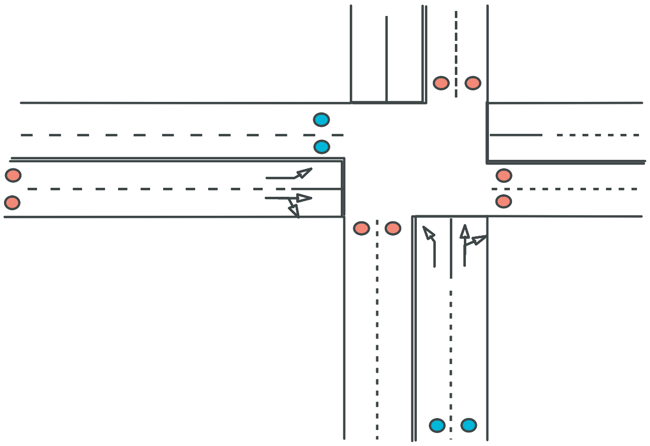


FIGURE A23 A common intersection detection layout in UTOPIA.

Communications

The communications network provides the communication links within UTOPIA architecture and between UTOPIA and external systems. The communications are based on a flexible WAN architecture, which supports several different media such as fiber optic, dedicated telecommunication lines, VPN based on DSL connections, and private copper cables; wireless technology; and various communication protocols (e.g., standard TCP/IP and proprietary serial protocol). Particularly for fully adaptive operations, UTOPIA requires a robust and reliable communications network between the local SPOT units and between the local level and the central system, with the minimal capacity of 9.6K bauds.

Special Features

Plan Selection Strategies

These traffic control strategies are suitable for networks with predictable TOD and DOW traffic patterns. Once a set of typical signal timing plans is defined (based on the historic traffic data from detectors) and stored in the system library, it can be activated by any of these three methods:

- Automatic pattern-matching plan selection—activation is automatically performed whenever a certain “traffic pattern” is recognized in the measured traffic data;
- Time-based plan selection—activation is based on date, time, and type of day criteria; and
- Manual mode—operator activates the signal timing plan manually.

The signal timing plan is implemented at the intersection level by the SPOT software. SPOT switches between signal timing plans using a “smooth” transition technique (i.e., the green splits and offsets are changed gradually to avoid discontinuity or jumps in the phase sequence). Also, if traffic control is executed through the plan selection strategies SPOT takes control of traffic signal priority for public transit, emergency, and VIP vehicles.

Traffic Light Priority Management

UTOPIA is able to assign absolute, weighted, and selective priority to buses and trams at signalized intersections. This function can also be extended to emergency and VIP vehicles. For public transit vehicles, traffic signal priority is implemented through:

- Functional integration with an automatic vehicle location/automated vehicle maintenance system,
- Local detectors (active and passive),
- Dedicated detectors managed by the UTOPIA PT Locator central functionality, and
- A combination of these methods.

In UTOPIA the priority requests are represented by *forecasting the arrival time* of the priority vehicles at the intersection. In general, the priority requests are prepared by the central level (automated vehicle maintenance or PT Locator) and forwarded to the local level, where the SPOT control function handles properly. When local detection is implemented, SPOT also generates the priority requests.

In all cases, the SPOT unit implements a distributed forecast function, which complements the central forecast functionality and consists of the local propagation of the arrival forecasts from SPOT to the downstream intersections along the priority vehicle route. Forecasts are promptly corrected by SPOT when priority vehicles are delayed at the traffic light.

To determine the level of priority, "weights" are assigned to specific vehicles (e.g., according to the line, direction, or vehicle adherence to the schedule) locally or centrally. In UTOPIA, public transit priority is achieved within the intersection optimization process and not as a result of post-processing actions. Optimization is carried out every 3 s; therefore, the system can react quickly to any changes in the predicted arrival time. When the vehicle has safely passed the intersection, the priority request is "cleared" by the SPOT unit.

In the definition of the intersection state, PT vehicles are considered in the same way as private vehicles; they are represented by equivalent "vehicle platoons," which appear as probability curves centred on the predicted arrival times. These curves become steeper as the vehicle approaches the intersection and the forecast variations decrease. UTOPIA begins to calculate the control strategy (stage duration, offset, etc.) when the public transit vehicle is approaching the intersection. In this way, it ensures that the traffic signal phases are managed in a way that minimizes the impact on other vehicles.

The SPOT control function is also responsible for recovering any disturbances to the local optimization strategy resulting from the priority request. For adaptive mode, the recovery action is based on a fine optimization of the waiting times on all the traffic movements. In the plan selection mode, the system is "re-hooked" gradually to the selected plan to compensate for the effects of the priority provision. The system can provide priority to emergency and VIP vehicles as long as these are equipped with on-board transmitters so that they can be detected. The priority in this case is managed at the local level and is based on vehicle–detector communication.

APPENDIX B

Survey Questionnaire

SURVEY FOR AGENCIES THAT UTILIZE ADAPTIVE TRAFFIC CONTROL SYSTEMS

The Transportation Research Board's National Cooperative Highway Research Program (NCHRP) has commissioned a study on Adaptive Traffic Control Systems (ATCS). The goal of the research is to synthesize the current state of practice on using these systems in the U.S. and selected foreign countries. We have less than 50 ATCS in the U.S. Yours is among the few. This means that your experience of working with an ATCS is very important to us. We need your opinion and experience to help us to assess the overall performance and applicability of ATCS in the U.S.

Please be assured that your responses will be kept in strictest confidence. We will aggregate them with all other responses.

Name:
Organization:
Position:
Address:
Phone:
Fax:
E-mail:

Section I: General Information

1. Please indicate the type of your agency:

   a. City government

   b. County government

   c. State government

   d. Regional organization (e.g., metropolitan planning organization)

   e. Federal government

   f. Consultant

   g. Other, please specify: __________________________

   Approximately, how many traffic signals does your agency operate? ________; and how many are under Adaptive Traffic Control System (ATCS)? _______

2. How would you characterize ATCS deployment at your agency?

   a. ATCS fully deployed (Year:___ Month:___) and working

   b. ATCS fully deployed (Year:___ Month:___) and turned off/removed (Year:__ Month:__)

   c. ATCS about to be deployed (Please specify expected time of full operations Y:__ M:__)

   d. ATCS was tested (Year:___ Month:___ Test duration:___) but never deployed

3. Please specify type of traffic control used before ATCS was installed. (Check all that apply.)

   a. Fixed-time coordinated control

   b. Actuated coordinated control

   c. Fixed-time isolated control
   d. Actuated isolated control
   e. Other, please specify: ____

4. How long did it take to get the ATCS installed (from time when funding was available until ATCS was fully operational)?
   a. Less than 3 months
   b. 3–6 months
   c. 6–12 months
   d. 1–2 years
   e. More than 2 years

5. Which ATCS(s) does your agency deploy? (Check all that apply.)
   a. ACS Lite; Version ____________
   b. LA ATCS; Version ____________
   c. OPAC; Version ____________
   d. RHODES; Version ____________
   e. SCATS; Version ____________
   f. SCOOT; Version ____________
   g. Other (Please specify): ____

6. Did you seriously consider other ATCSs before you selected this one for installation in your jurisdiction? Why did you reject the other(s) in favor of this one?
   ____
   ____
   ____

7. How familiar do you consider yourself with your ATCS?
   a. I know the system very well [for multiple systems specify which one(s) __________]
   b. I have a good working knowledge [for multiple systems specify which one(s) ________]
   c. I understand it but am no specialist [for multiple systems specify which one(s) ________]
   d. I have a vague understanding [for multiple systems specify which one(s) __________]
   e. Unfamiliar [for multiple systems specify which one(s) __________]

8. How many traffic signal operations staff (for all traffic signals) are in your organization?
   a. Engineers __________
   b. Timing technicians __________
   c. Field technicians __________
   d. Maintenance technicians __________
   e. Others __________

9. How many times have new intersections been added under the ATCS umbrella since its initial deployment? (Please specify the reason.)

   a. None

   b. Once __Major expansion __New signals added within the system

   c. Twice __Major expansion __New signals added within the system

   d. 3+ times __Major expansion __New signals added within the system

10. Which of the following type(s) of network configuration best represent your typical ATCS deployment?

    a. Arterial

    b. Grid

    c. Radial

    d. Combination of the above

    e. Other, please specify: ____

11. Why did you agency install an ATCS? Please rank the reasons provided below according to their importance? (1 for the least important; 9 for the most important):

    a. Reducing/eliminating costs of retiming traffic signals
       #__

    b. Handling oversaturated traffic conditions
       #__

    c. Handling traffic special events
       #__

    d. Handling high day-to-day and within-a-day traffic variability
       #__

    e. Handling conflicts between vehicular traffic and other modes (pedestrian, transit, etc.)
       #__

    f. Serving as a testbed/early deployer of innovative signal control method
       #__

    g. Availability of funding for capital ITS projects
       #__

    h. Expecting significant operational savings and/or high benefit/cost ratio #__

    i. Other (please specify): ____ #__

12. How satisfied are you, in general, with the adaptive aspect of your ATCS deployment?

    a. Very satisfied

    b. Somewhat satisfied

    c. Neutral

    d. Somewhat dissatisfied

    e. Not satisfied at all

13. If your ATCS does not operate on all signals in your jurisdictions at all times of day, why haven't you expanded it to do so?
____
____
____

Section II: System Requirements

Detection

14. What type of detection technology do you use for your ATCS? (Check all that apply.)

    a. Inductive loops

    b. Video detection

    c. Radar detection

    d. Other (please specify): ________________________________

15. How would you characterize the level of detection needed for the proper functioning of your ATCS?

    a. More detectors than actuated traffic control systems

    b. Number of detectors is similar to the number used by actuated traffic control systems

    c. Fewer detectors than used by actuated traffic control systems

16. How many detectors does your ATCS use for a typical 4-leg 12-movement (a lane per movement) intersection:____? Please provide additional description here:
____
____

17. Where are detectors typically placed in your ATCS deployment?

    a. Upstream, ____ ft from a downstream intersection

    b. Stop-line

    c. Mid-block, ____ ft from a downstream intersection

    d. Combination of ____ and ____

18. Where left-turn detectors are typically placed in your ATCS deployment?

    a. Filter detection (detector is placed in the destination lane of a left-turn movement)

    b. Stop-line detection

    c. Behind stop-line detection (2–3 car lengths behind; triggers protected left only for 2–3 + cars)

    d. Upstream detection, _____ ft from downstream intersection

    e. Combination of ____ and ____

    f. No left-turn detectors

19. How does your ATCS work with minor detector malfunctioning (only a few detectors fail)?

    a. Very well

    b. Acceptably

  c. Neutrally

  d. Poorly

  e. Very poorly

20. What happens to your ATCS operations when many detectors fail?

  a. ATCS continues to operate as if nothing happened

  b. ATCS triggers an alarm and notifies operators

  c. ATCS switches to an “off-line” mode by implementing Time-Of-Day plans

  d. Combination of ____ and ____

  e. Other (please describe): ____

Hardware

21. Does your ATCS use hardware with which you and your colleagues are familiar?

  a. Central controller (server) __Yes __No

  b. Local controllers __Yes __No

  c. Additional hardware __Yes __No

  Please specify additional hardware: ____

22. What type of traffic controllers are used by your ATCS? (Check all that apply.)

  a. NEMA TS-1, # of controllers ____

  b. NEMA TS-2, # of controllers ____

  c. 170, # of controllers ____

  d. 2070, # of controllers ____

  e. Other, please specify: ________________________

Software

23. What type of Operating System (OS) does your ATCS run?

  a. Windows-based OS

  b. Unix-based OS

  c. Open VMS

  d. Other, please specify: ____________________

24. How user-friendly is your ATCS’ software?

  a. Very friendly

  b. Friendly

c. Neutral

d. Unfriendly

e. Very unfriendly

Communications

25. How dependent is your ATCS on reliable communications? Rate the level of importance of the communications for your deployment? (1- the most important, 3 - the least important):

    a. Communications between elements at the intersection _____

    b. Peer-to-peer communications _____

    c. Field controller to central system communications _____

26. What type of transmission media does your ATCS use for communication between central hardware/software and field traffic controllers? (Check all that apply.)

    a. Twisted pair

    b. Telephone line

    c. Coaxial cable

    d. Fiber optic

    e. Microwave (terrestrial or satellite)

    f. Wireless (application protocol or broadband systems)

    g. Other, please specify: ________________________

27. What type of transmission media does your ATCS use for communication between field traffic controllers? (Check all that apply.)

    a. Twisted pair

    b. Telephone line

    c. Coaxial cable

    d. Fiber optic

    e. Microwave (terrestrial or satellite)

    f. Wireless (application protocol or broadband systems)

    g. Other, please specify: ________________________

    h. Not applicable

28. How do you compare ATCS's communications to your communications of regular traffic signals?

    a. More problems with ATCS communications

    b. Similar to communications of regular traffic signals

    c. Fewer problems with ATCS communications

<u>Other</u>

29. Which of the following traffic control management systems is integrated in your ATCS? (Specify all that apply.)
    a. ACTRA
    b. I2 (Icons)
    c. MIST
    d. Other, please specify: ___________________________
    e. We do not use any traffic control management system
    f. Our ATCS is not integrated with our traffic control management system (specify which one __________) because
    ____
    ____
    ____

30. What is the predominant design speed on the network where your ATCS is deployed?
    a. Less than 30 mph
    b. Between 30 mph and 45 mph
    c. More than 45 mph
    d. Combination of ____ and ____and____

31. Is your ATCS able to report malfunctions and other diagnostics of its hardware and software components?
    a. Yes
    b. No
    c. Generally yes, but it does not report on ____

32. Do you find traffic metrics (traffic flows, level of service, degree of saturation, etc.) reported by your ATCS useful for other traffic engineering purposes?
    a. Yes, please specify: ____
    b. No

Section III: Institutional Issues

<u>Training</u>

33. What is the best estimate of the level of effort, by vendor/consultant, to train your staff to operate the ATCS: Person-days _____?

34. Was the training provided by vendor/consultant adequate? If not, what was the major reason for inadequacy?
    a. Yes, the training was adequate
    b. No, vendor/consultant did not have enough expertise
    c. No, there was not enough interest for the training at our agency
    d. No, vendor/consultant was not interested in providing the training
    e. No, training was too expensive
    f. No, because (please specify): ____

35. How understandable are working principles of your ATCS to you and your colleagues?
    a. Very easy
    b. Easy
    c. OK
    d. Difficult
    e. Very difficult
36. Where does expertise come from to operate/maintain your ATCS deployment currently?
    a. In-house expertise
    b. We contract out
    c. Combination of a. and b., please describe: ____________________
37. Is your agency willing to improve in-house expertise to fully utilize your ATCS potential? If not, what are major obstacles to obtain such expertise? (Check all that apply.)
    a. Yes, we would like to get enough expertise to fully operate ATCS in-house
    b. No, we do not have enough staff
    c. No, cost of such training program would be prohibitively expensive
    d. No, there is not enough interest for ATCS at our agency
    e. No, the ATCS does not deserve that much attention—only small % of signals is under ATCS
    f. No, because (please specify): ____________________

Operations

38. Do you have enough staff to operate and maintain the ATCS to its fullest potential?
    a. Yes
    b. No—how much more do you need and what type? ____________________
39. Is your annual budget for operations and maintenance of traffic signals large enough to cover expenses for your ATCS to its fullest potential?
    a. Yes
    b. No
40. How do you perceive operations of your ATCS (hardware, communications, and software)?
    a. Much more demanding than operations of regular traffic signals
    b. More demanding than operations of regular traffic signals
    c. Same as operations of regular traffic signals
    d. Less demanding than operations of regular traffic signals
    e. Much less demanding than operations of regular traffic signals

41. What is the best estimate of the level of effort, by the vendor/consultant, to make the ATCS operational: Person-days _____?

42. How would you characterize technical support by your ATCS vendor for your deployment?

    a. Very good

    b. Good

    c. Neutral

    d. Poor

    e. Very poor

43. What are the major problems with the technical support for your ATCS? (Check all that apply.)

    a. No local consultants to provide technical support

    b. Technical support is too expensive

    c. Vendor providing technical support does not have enough expertise on our ATCS

    d. Other, please specify: ____

    e. Not applicable—no problems with technical support

44. What are the major traffic operation features that your ATCS handles well (explain why, in your opinion)?
    ____
    ____
    ____

45. What are the major traffic operation features that your ATCS does NOT handle well (explain why not, in your opinion)?
    ____
    ____
    ____

<u>Maintenance</u>

46. How do you perceive maintenance of your ATCS (hardware, communications, and software)?

    a. Much more demanding than maintenance of regular traffic signals

    b. More demanding than maintenance of regular traffic signals

    c. Same as maintenance of regular traffic signals

    d. Less demanding than maintenance of regular traffic signals

    e. Much less demanding than maintenance of regular traffic signals

47. Please describe any additional maintenance required to effectively operate an ATCS?
    ____
    ____
    ____

48. Which component of your ATCS deployment is the most challenging to maintain and why?

    a. Detection, because ____

    b. Communication, because ____

    c. Hardware, because ____

d. Software, because ____

e. Licensing, because ____

f. Other, please specify: ____

49. Is there any other institutional issue that you would like to report?
____
____
____
____
____

Section IV: Implementation Benefits & Costs

Costs

50. Please characterize pricing of licensing requirements for further expansion of your ATCS?

a. Prohibitively expensive

b. Expensive

c. Neutral

d. Affordable

e. Inexpensive

f. Not applicable

Please justify your response
____
____
____

51. Please specify the total ATCS installation costs (or the best estimate): $__________

(Do not include intersection upgrade or similar costs.)

52. What percentage of your typical annual budget would you estimate is spent on physical maintenance of your ATCS deployment? _________(Do not include addition of new signalized intersections or similar costs.)

53. What are your best estimates of per-intersection annual costs of maintaining optimal signal timings (e.g., consulting, hardware, and software costs) for:

a. ATCS deployment $ ________

b. Non-ATCS deployment $ ________

Evaluation

54. How was ATCS performance evaluated?

a. In-house

b. By an independent evaluator

c. Not applicable—there was no evaluation

55. What type of evaluation study was conducted? (Check all that apply.)

    a. Field evaluation

    b. Evaluation through microsimulation

    c. “Before ATCS and after ATCS” study

    d. “ATCS On and ATCS Off” study—(TOD plans operate when ATCS is turned off)

    e. Not applicable

56. Which performance measures were collected in the evaluation study? (Check all that apply.)

    a. Arterial travel time/delay

    b. Number of stops

    c. Intersection delay

    d. Queue lengths

    e. Average speeds

    f. Others, please specify: ____

    g. Not applicable

57. For which of these performance measures was ATCS shown to be significantly better than conventional traffic control? (Check all that apply.)

    a. Arterial travel time/delay

    b. Number of stops

    c. Intersection delay

    d. Queue lengths

    e. Average speeds

    f. Others, please specify: ____

    g. Not applicable

58. Based on your ATCS evaluation study—how does ATCS compare to previous traffic control?

    a. ATCS is much better

    b. ATCS is better

    c. Neutral

    d. Previous traffic control was better

    e. Previous traffic control was much better

    f. Not applicable

Benefits

59. If the corridors on which the ATCS operates experience over saturation, how would you rate the operation of the ATCS in response to these traffic conditions?

    a. ATCS prevents or eliminates oversaturation

    b. ATCS eliminates or reduces the extent of the periods of oversaturation

    c. ATCS adversely affects the traffic conditions during periods of oversaturation

    d. Other:____

    f. Oversaturation is very rare on the corridors operated by our ATCS

60. Based on your performance measures, when are ATCS operations proven to be the most effective?

    a. Peak periods

    b. Off-peak periods

    c. Shoulders of peak periods

    d. Other: ____

61. Has the level of performance of ATCS been sustained since its installation?

    a. Yes

    b. No; why not? Any specific reason? ________________________________

62. Are there any other costs or benefits related to ATCS deployment that you would like to report?

    a. Benefits
    ____
    ____
    ____

    b. Costs
    ____
    ____
    ____

Public Perception

63. How effective was a public education campaign conducted by your agency along with your ATCS deployment?

    a. Very effective

    b. Somewhat effective

    c. Neutral

    d. Not very effective

    e. Not effective

    f. Not applicable—there was no public education campaign

64. Are the results of public perception survey supportive of the ATCS?

    a. Clearly supportive

    b. Somewhat supportive

c. Neutral

d. Somewhat not supportive

e. Not supportive

f. Not applicable—there was no public perception survey

Section V: Final Comments

65. What were the biggest surprises in your early ATCS deployment?

a. Good surprises____

b. Bad surprises ____

66. Would you install the same ATCS again in another location? If not, why not? (Check all that apply.)

a. Yes, we would probably install the same ATCS again

b. No, other ATCSs seem to work better

c. No, installation costs are too high

d. No, operations and maintenance costs are too high

e. No, we do not have enough expertise within the agency

f. No, technical support from vendor is weak

g. No, ATCS deployment is not necessary—we did not see expected benefits

h. No, because (please specify): __________________________________

67. In hindsight, what would you have done differently during the implementation of your ATCS?

____
____
____

68. Do you have an evaluation case study of your ATCS that you would be willing to share with us? If you answer yes, the consultant will contact you via e-mail to arrange delivery and potential further interviews regarding the case study.

a. Yes

b. No

69. Do you have any other information that you believe would be helpful to this study? If so, please indicate it in the blank provided below:

____
____
____
____
____
____

Thank you for your help in completing this survey. Your responses will help provide insights into how to better understand ATCS. If you have any questions regarding the survey, please contact Aleksandar Stevanovic, aleks@trafficlab.utah.edu, 801-671-2868. You can mail any documentation that you might feel will be helpful to this study to the following address: Aleksandar Stevanovic, 1192 University Village, Salt Lake City, UT 84108.

APPENDIX C

Bibliography of Adaptive Traffic Control Systems

ACS LITE

Adaptive Control Software, Report No. HRTS-04-037, Turner–Fairbank Highway Research Center, Washington, D.C., Dec. 2003.

Chatila, H.F. and Z. Li, *US-95 ACS Lite System Evaluation,* Report TG 07188.00, The Transpo Group, Boise, Idaho, Nov. 29, 2007, 21 pp.

Crenshaw, P., "ACS Lite," presented at the TRB A3A18 Meeting, 2000 Midyear Meeting Minutes, Seattle, Wash., July 9–10, 2000.

Curtis, E., "ACS Lite: The Next Generation of Traffic Signal Control," presented at the Winter Workshop: Adding to Your Traffic Engineering Toolkit, Columbus, Ohio, Feb. 28, 2007.

Gettman, D., "ACS Lite FHWA Adaptive Control for Closed-Loop Systems," presented at the ITE Annual Meeting, Melbourne, Australia, 2005.

Gettman, D., "ACS Lite Performance Measures," presented at the TRB Midyear Traffic Signal Systems Committee Meeting, Performance Measures Workshop, Las Vegas, Nev., July 10–13, 2005.

Gettman, D., "ACS Lite Performance Measures," presented at the TRB Annual Traffic Signal Systems Committee Meeting, Performance Measures Workshop, Washington, D.C., Jan. 22–26, 2006.

Ghaman, R., D. Gettman, L. Head, and P.B. Mirchandani, "Adaptive Control Software for Distributed Systems," *Proceedings of the 28th Annual Conference of the IEEE Industrial Electronics Society* (*IECON 02*), Sevilla, Spain, Nov. 5–8, 2002, Vol. 4, pp. 3103–3106.

Ghaman, R., D. Gettman, and S. Shelby, "ACS Lite Project Overview," presented at the TRB Annual Meeting, Adaptive Traffic Signal Control Workshop, Washington, D.C., Jan. 11–15, 2004.

Ghaman, R.S., "ACS Lite FHWA Adaptive Control for Closed-Loop Systems," presented at the 2nd Baltimore Regional Traffic Signal Forum, Baltimore, Md., Dec. 14, 2005.

Ghaman, R., "Adaptive Control Software—Lite Some Early Results," presented at the TRB Midyear Traffic Signal Systems Committee Meeting, Operating Traffic Signal Systems in Oversaturated Conditions Workshop, Woods Hole, Mass., July 10–13, 2006.

Ghaman, R.S., "Enhancing Signal Timing with Adaptive Control Software Lite," *Institute of Transportation Engineers Journal,* Vol. 76, No. 8, Aug. 2006, pp. 26–29.

Ghaman, R., "Adaptive Signal Control," presented at the Traffic Signal Forum, Baltimore, Md., Mar. 14, 2007.

Jain, K., P. Silberman, and Z.A. Sabra, Adaptive Control Software—LITE Before and After Traffic Analysis Report State Highway 70—City of Bradenton, Florida, Sep. 2006.

Luyanda, F., D. Gettman, L. Head, S. Shelby, D. Bullock, and P. Mirchandani, "ACS Lite Algorithmic Architecture: Applying Adaptive Control System Technology to Closed-Loop Traffic Signal Control Systems," *Transportation Research Record: Journal of the Transportation Research Board, No. 1856,* Transportation Research Board of the National Academies, Washington, D.C., 2003, pp. 175–184.

Sabra, Z.A., Wang & Associates, Inc., Adaptive Control Software—LITE Before and After Traffic Analysis Report Hamilton Road—City of Gahanna, Ohio, Nov. 2005.

Sabra, Z.A., Wang & Associates, Inc., Adaptive Control Software—LITE Before and After Traffic Analysis Report Main Street—El Cajon, California, Apr. 2007.

Shelby, S.G., "Single Intersection Evaluation of Real-Time Adaptive Traffic Signal Control Algorithms," *Transportation Research Record: Journal of the Transportation Research Board, No. 1867,* Transportation Research Board of the National Academies, Washington, D.C., 2004, pp. 183–192.

Shelby, S.G., "Resonant Cycles in Traffic Signal Control," presented at the TRB Midyear Traffic Signal Systems Committee Meeting, Toronto, ON, Canada, July 26, 2004.

Shelby, S.G., D.M. Bullock, and D. Gettman, "Resonant Cycles in Traffic Signal Control," *Transportation Research Record: Journal of the Transportation Research Board, No. 1925,* Transportation Research Board of the National Academies, Washington, D.C., 2005, pp. 215–226.

Shelby, S.G., D.M. Bullock, D. Gettman, R.S. Ghaman, Z.A. Sabra and N. Soyke, "Overview and Performance Evaluation of ACS Lite—Low Cost Adaptive Signal Control System," presented at the 87th Annual Meeting of the Transportation Research Board, Washington, D.C., Jan. 13–17, 2008, 17 pp.

Shelby, S., "Summary of ACS Lite," presented for the National Transportation Operations Coalition Web Cast Series, Washington, D.C., Mar. 27, 2008.

Thompson, C.D., P. Silberman, and Z.A. Sabra, Adaptive Control Software—LITE Before and After Traffic Analysis Report State Highway 6—City of Houston, Tex., Mar. 2006.

BALANCE

Balance Product Information, GEVAS software Systementwicklung und Verkehrsinformatik GmbH, Munchen, Germany, 11 pp.

Braun, R., C. Kemper, and F. Weichenmeier. "Travolution—Adaptive Urban Traffic Signal Control with an Evolutionary Algorithm," *Proceedings of the 4th International Symposium Networks for Mobility 2008,* Stuttgart, Germany, Sep. 24–25, 2008.

Braun, R., C. Kemper, F. Weichenmeier, C. Menig, and J. Wegmann, "Comparing Different Adaptive Traffic Signal Control Optimization Methods—Field Test Results," *Proceedings of the 15th World Congress on ITS,* New York, N.Y., Nov. 16–20, 2008, 12 pp.

Friedrich, B., T. Sachse, M. Hoops, W. Jendryschik, and G. Reichert, "Balance and Varia Methods for Traffic Adaptive Control," *Proceedings of the Second World Congress on the ITS,* Yokohama, Japan, 1995, pp. 2356–2361.

Friedrich, B., "Adaptive Signal Control: An Overview," *Proceedings of the 9th Meeting of the Euro Working Group Transportation,* Italy, 2002, pp. 571–574.

LA DOT ATCS

Adaptive Traffic Control System, Operator Manual and Reference, Client version: 2.6, Department of Transportation, City of Los Angeles, Calif., Sep. 2006.

Hu, K., "LADOT's Adaptive Traffic Control System (ATCS)," presented at the TRB Annual Meeting, Adaptive Traffic Signal Control Systems Workshop, Washington, D.C., Jan. 9, 2000.

Hu, K., "LADOT's Adaptive Traffic Control System (ATCS)," presented at the 80th TRB Annual Meeting of the Transportation Research Board, Adaptive Traffic Signal Control Systems Workshop, Washington, D.C., Jan. 7, 2001.

Mogharabi, A. and D. Roseman, "Public Private ATCS/ITS Implementation," *Proceedings of the ITE Western District Annual Meeting,* Denver, Colo., July 12–15, 2009, 9 pp.

MOTION

Busch, F. and G. Kruse, "MOTION for SITRAFFIC—A Modern Approach to Urban Traffic Control," *Proceedings of the IEEE Conference on Intelligent Transportation Systems,* ITSC, 2001, pp. 61–64.

Kroyer, B., "Adaptive Traffic Light Control in Denmark—Motion," presented at the Nordisk Trafiksignalkonferens, Stockholm, Sweden, May 7, 2007.

Kruse, G., "MOTION—Signal Control for Urban Road Networks," presented at the TRB Midyear Traffic Signal Committee Meeting, Adaptive Traffic Signal Control Workshop, Pacific Grove, Calif., July 12–14, 1998.

Mueck, J., "Recent Developments in Adaptive Control Systems in Germany," *Proceedings of the 12th World Congress on ITS,* San Francisco, Calif., Nov. 6–10, 2005, 11 pp.

Mueck, J., "The German Approach to Adaptive Network Control," *Proceedings of the 7th European Congress and Exhibition on Intelligent Transport Systems and Services,* Geneva, Switzerland, June 4–6, 2008, 6 pp.

Mueck, J., "The 'German' Approach to Adaptive Network Control," *Traffic Technology International,* Erlangen, Germany, Aug. 2008, 13 pp.

OPAC

Andrews, C.M., S.M. Elahi, and J.E. Clark, "Evaluation of New Jersey Route 18 OPAC/MIST Traffic Control System," *Transportation Research Record 1603,* Transportation Research Board, Washington, D.C., 1997, pp. 150–155.

Chen, H., C.C. Liu, S.L. Cohen, P.J. Tarnoff, and R.L. Sumner, "An Adaptive Control Strategy for Signalized Intersections," *Proceedings of the North American Conference on Microcomputers in Transportation,* ASCE, Reston, Va., 1987, pp. 55–63.

Eghtedari, A.G., "Measuring the Benefits of Adaptive Traffic Signal Control: Case Study of Mill Plain Blvd., Vancouver, Washington," 85th Annual Meeting of the Transportation Research Board, No. 06-0111, Washington, D.C., Jan. 22–26, 2006, 16 pp.

Gartner, N.H., *Demand-Responsive Decentralized Urban Traffic Control,* Report DOT/RSPA/DPB-50/81/24, U.S. Department of Transportation, Washington, D.C., 1982.

Gartner, N.H., F.J. Pooran, and C.M. Andrews, "Implementation and Field Testing of the OPAC Adaptive Control Strategy in RT-TRACS," *Journal of the Transportation Research Board,* Washington, D.C., 2002, pp. 148–156.

Gartner, N.H., "Optimized Policies for Adaptive Control (OPAC), Session 1: Principles of Operation," presented at the TRB Annual Meeting, Adaptive Traffic Signal Control Systems Workshop, Washington, D.C., Jan, 7, 2001.

Gartner, N.H., F.J. Pooran, and C.M. Andrews, "Implementation of the OPAC Adaptive Control Strategy in a Traffic Signal Network," *IEEE Intelligent Transportation Systems Conference Proceedings,* Oakland, Calif., Aug. 25–29, 2001, pp. 195–200.

McNally, M.G., J.E. Moore, and C.A. MacCarley, *Documentation of the Irvine Integrated Corridor Freeway Ramp Metering and Arterial Adaptive Control Field Operational Test,* Report UCB-ITS-PRR-2001-02, Institute of Transportation Studies, University of California, Berkeley, 2001, 161 pp.

Moser, A. and K.A. Jacobs, "RT-TRACS Adaptive Signal Operations, Maintenance and Lessons Learned," *Proceedings of the 15th World Congress on ITS,* New York City, N.Y., Nov. 16–20, 2008, 12 pp.

PB Farradyne Inc., *Evaluation of New Jersey Route 18 OPAC/MIST System,* U.S. DOT Contract DTFH61-92-C-00001, Federal Highway Administration, Washington, D.C., Sep. 1996, 56 pp.

Pooran, F., "RT-TRACS Adaptive Control Algorithms, VFC-OPAC," presented at the TRB A3A18 Midyear Meeting, Adaptive Traffic Signal Control Systems Workshop, Pacific Grove, Calif., July 12–14, 1998.

Pooran, F., "Optimized Policies for Adaptive Control (OPAC)," presented at the TRB Annual Meeting, Adaptive Traffic Signal Control Systems Workshop, Washington, D.C., Jan. 9, 2000.

Pooran, F., "Optimized Policies for Adaptive Control (OPAC), Session II—Equipment Requirements," presented at the TRB Annual Meeting, Adaptive Traffic Signal Control Systems Workshop, Washington, D.C., Jan, 7, 2001.

Yauch, P.J., "Pinellas County's Adaptive Control Systems," presented at the TRANSPO 2006, Palm Harbor, Fla., Nov. 27–30, 2006.

RHODES

Ghaman, R., D. Gettman, L. Head, and P.B. Mirchandani, "Adaptive Control Software for Distributed Systems," *Proceedings of the 28th Annual Conference of IEEE Industrial Electronics Society,* Sevilla, Spain, Vol. 4, Nov. 5–8, 2002, pp. 3103–3106.

Head, K.L., P.B. Mirchandani, and D. Shepherd, "A Hierarchical Framework for Real-Time Traffic Control," *Transportation Research Record 1360,* Transportation Research Board, National Research Council, Washington, D.C., 1992.

Head, L. and P. Mirchandani, "The RHODES Prototype: A Technical Review," presented at the TRB A3A18 Midyear Meeting, Adaptive Traffic Signal Control Systems Workshop, Asilomar, Pacific Grove, Calif., July 12–14, 1998 [Online]. Available: http://www.signalsystems.org.vt.edu/documents/July1998AnnualMeeting/rhodes.pdf.

Head, L. and P. Mirchandani, "RHODES: Fundamental Principles," presented at the 79th Annual Meeting of the Transportation Research Board, Adaptive Signal Control Systems Workshop, Washington, D.C., Jan. 9–13, 2000.

Head, L. and P. Mirchandani, "RHODES: Equipment Requirements" presented at the 80th Annual Meeting of the Transportation Research Board, Adaptive Signal Control Systems Workshop, Washington, D.C., Jan. 7–11, 2001.

"ICONS Advanced Traffic Management System (ATMS) & RHODES Traffic Adaptive Control Program," The Institute of Arizona [Online]. Available: http://www.dot.state.mn.us/metro/trafficeng/signals/files/rhodes.pdf.

Intelligent Transportation Systems, *IEEE ITS Society Newsletter,* Vol. 7, No. 1, Mar. 2005, 30 pp.

Lucas, D.E., P.B. Mirchandani, and K.L. Head, “Remote Simulation to Evaluate Real-time Traffic Control Strategies,” *Transportation Research Record: Journal of the Transportation Research Board, No. 1727,* Transportation Research Board, National Research Council, Washington, D.C., 2000, pp. 95–100.

Metropolitan Transportation Commission, City of Sunnyvale, Department of Public Works, Division of Transportation and Traffic “2.4 GHz Spread Spectrum Radio System Installation in Sunnyvale,” presented at the Technology Transfer Seminar, Oct. 25, 2005.

Mirchandani, P., L. Head, A. Knyazyan, and W. Wu, “An Approach Towards the Integration of Bus Priority, Traffic Adaptive Signal Control, and Bus Information/Scheduling System,” *Lecture Notes in Economics and Mathematical Systems,* 2000.

Mirchandani, P. and L. Head, “RHODES Traffic-Adaptive Control Systems,” presented at the TRB Annual Meeting, Adaptive Signal Control Systems Workshop, Washington, D.C., Jan. 7–11, 2001.

Mirchandani, P. and L. Head, “A Real-Time Traffic Signal Control System: Architecture, Algorithms, and Analysis,” *Transportation Research Part C: Emerging Technologies,* Vol. 9, No. 6, Dec. 2001, pp. 415–432.

Mirchandani, P. and D.E. Lucas, “Integrated Transit Priority and Rail/Emergency Preemption in Real-Time Traffic Adaptive Signal Control,” *Journal of Intelligent Transportation Systems: Technology, Planning, and Operations,* Vol. 8, No. 2, Apr 1, 2004, pp. 101–115.

Mirchandani, P., “TRANSPORTATION + ITS + PNT,” presented at the NCRST-F Workshop, Ohio State University, Columbus, Nov. 30–Dec. 1, 2005.

Mirchandani, P., “Next Generation Real-time Traffic Adaptive Management Systems,” presented at Delft University of Technology, Delft, The Netherlands, Apr. 15, 2008.

Morales, J.M., “Proceedings and Recommendations,” Proceedings of the Workshop on Models in Support of Advanced Traffic Management Systems (ATMS), Palm Coast, Fla., May 16–19, 1999, 44 pp.

Tomlinson, A. and L. Bull, *Towards Distributed Adaptive Control for Road Traffic Junction Signals Using Learning Classifier Systems,* Report UWELCSG02-004, UWE Learning Classifier Systems Group, University of the West of England, Bristol, U.K., 2004.

Warberg, A., J. Larsen, and R.M. Jorgensen, *Green Wave Traffic Optimization—A Survey,* Report IMM 2008/01, Informatics and Mathematical Modelling, Technical University of Denmark, Lyngby, Feb. 8, 2008.

Yu, X.H. and W.W. Recker, “Stochastic Adaptive Control Model for Traffic Signal Systems,” *Transportation Research Part C: Emerging Technologies,* Vol. 14, No. 4, Aug. 2006, pp. 263–282.

SCATS

Chau, C., *Adaptive Traffic Control System Using SCATS,* Land Development and Transportation Division Engineering Department, Chula Vista, Calif., May 2003, 51 pp.

Daizong, L., Comparative Evaluation of Dynamic TRANSYT & SCATS-Based Signal Control Systems Using PARAMICS Simulation, M.S. dissertation, National University of Singapore, Singapore, 2003.

Datta, T.K., “Innovations in Traffic Signal Systems,” presented during Advanced Traffic Signal Systems Course, College of Engineering, Wayne State University, Detroit, Mich., 2003.

Department of Planning and Infrastructure of NT, “SCATS and Darwin Traffic Signals” [Online]. Available: http://www.“darwin.nt.gov.au/aboutcouncil/council_overview/documents/Cou31stagn-AttachmenttoItem9.1.pdf.

Fehon, K.J., S.E. Moore, and B.J. Negus, “Validation of SCATSIM,” *Proceedings of the Second International Conference on Road Traffic Control,* Institution of Electrical Engineers, London, U.K., No. 260, Apr. 1986, pp. 123–126.

Fitts, A.J., “Benefits of Traffic Signal Reviews Using Computer Aids,” *Proceedings of the 15th World Congress on ITS,* New York City, N.Y., Nov. 16–20, 2008, 8 pp.

Gross, N.R., “SCATS Adaptive Traffic System,” presented at the TRB A3A18 Midyear Meeting, Adaptive Signal Control Systems Workshop, Washington, D.C., July 1998.

Gross, N.R., “SCATS Adaptive Traffic System Session 1—Principles,” presented at the 79th Annual Meeting of the Transportation Research Board, Adaptive Signal Control Systems Workshop, Washington, D.C., Jan. 2000.

Gross, N.R., “SCATS Adaptive Traffic System Session 2—Equipment Requirements,” presented at the 79th Annual Meeting of the Transportation Research Board, Adaptive Signal Control Systems Workshop, Washington, D.C., Jan. 2000.

Gross, N.R., “Workshop on Adaptive Traffic Signal Control—Equipment Requirements for Adaptive Control—SCATS,” presented at the 80th Annual Meeting of the Transportation Research Board, Adaptive Signal Control Systems Workshop, Washington, D.C., Jan. 7–11, 2001.

Hunter, M.P., S.K. Wu, and H.K. Kim, “Evaluation of Signal System Improvements Cobb County ATMS Phase III,” presented at the 85th Annual Meeting of the Transportation Research Board, Performance Measures Workshop, Washington, D.C., Jan. 22–26, 2006.

Keong, C.K., “The GLIDE System—Singapore’s Urban Traffic Control System,” *Transport Reviews,* Vol. 13, No. 4, 1993, pp. 295–305.

Kergaye, C., A. Stevanovic, and P.T. Martin, “Comparison of Before/After versus Off/On Adaptive Traffic Control Evaluations: Park City Case Study,” *Proceedings of the 88th TRB Annual Meeting,* Paper No. 09-3452, Washington, D.C., Jan. 11–15, 2009.

Lappin, J.E., M. Petrella, S. Bricka, and M.P. Hunter, “Driver Satisfaction with an Urban Arterial after Installation of an Adaptive Signal System,” No. 06-2197, 85th Annual Meeting Compendium Papers, CD, Washington, D.C., Jan. 22–26, 2006, 16 pp.

Liu, D. and R.L. Cheu, “Comparative Evaluation of Dynamic TRANSYT and SCATS-Based Signal Control Logic Using Microscopic Traffic Simulations,” Preprint CD-ROM, prepared for the 83rd Annual Meeting of Transportation Research Board, Washington, D.C., Jan. 2004.

Lowrie, P.R., “The Sydney Co-ordinated Adaptive Traffic System—Principles, Methodology, Algorithms,” *Proceedings of the International Conference on Road Traffic Signaling,* Institution of Electrical Engineers, London, U.K., Vol. 207, 1982, pp. 67–70.

Lowrie, P., D. Quail, N. Rubbi, and C. Skinner, *Traffic Simulation of Networks Controlled by SCATS,* Roads and Traffic Authority (RTA) of New South Wales, Australia, n.d.

Luk, J.Y.K., A.G. Sims, and P.R. Lowrie, “SCATS—Application and Field Comparison with a TRANSYT Optimised Fixed Time System,” *Proceedings of the International Conference on Road Traffic Signaling,* Institution of Electrical Engineers, London, U.K., Vol. 207, 1982, pp. 71–74.

Luk, J., A. Sims, and P. Lowrie, "Evaluating Four Methods of Area Traffic Control—The Parramatta Experiment," *Australian Journal of Instrumentation and Control,* Vol. 39, No. 4, Aug. 1983, pp. 75–77.

Luk, J.Y.K., "Two Traffic-Responsive Area Traffic Control Methods: SCAT and SCOOT," *Traffic Engineering & Control,* Vol. 25, No. 1, Jan. 1984, pp. 14–22.

Martin, P.T., "SCATS, An Overview," presented at the 80th TRB Annual Meeting, Adaptive Signal Control Systems Workshop, Washington, D.C., Jan. 7–11, 2001.

Maze, T.H., D. Kroeger, and M. Berndt, *Trucks and Twin Cities Traffic Management,* Report MN/RC-2005-21, Minnesota Department of Transportation, St. Paul, June 2005.

Partners in Motion, Minnesota Department of Transportation Metropolitan Division, Roseville [Online]. Available: http://www.ntl.bts.gov/lib/jpodocs/brochure/353.pdf.

Peters, J.M., J. McCoy, and R.L. Bertini, "Evaluating an Adaptive Signal Control System in Gresham," *Proceedings of the Institute of Transportation Engineers District 6 Annual Meeting,* Portland, Ore., July 15–18, 2007, 8 pp.

Petrella, M., S. Bricka, M. Hunter and J. Lappin, *Measuring Driver Satisfaction with an Urban Arterial After Installation of an Adaptive Signal System,* Report EDL No. 14298, Intelligent Transportation Systems Joint Program Office, Federal Highway Administration, Washington, D.C. [Online]. Available: http://www.itsdocs.fhwa.dot.gov//JPODOCS/REPTS_TE/14298_files/14298.pdf.

Piotrowicz, G., "SCATS Operational Experience at the Road Commission for Oakland County," presented at the 80th Annual Meeting of the Transportation Research Board, Adaptive Signal Control Systems Workshop, Washington, D.C., Jan. 7–11, 2001.

Piotrowitcz, G., "SCATS Field Experience at the Road Commission for Oakland County," presented at the 83rd TRB Annual Meeting, Adaptive Signal Control Systems Workshop, Washington, D.C., Jan. 11–15, 2004.

Piotrowitcz, G., "Analysis of Wireless Communications Options for SCATS," *Proceedings of the 15th World Congress on Intelligent Transport Systems,* New York, N.Y., Nov. 16–20, 2008, 4 pp.

SCATS Adaptive Traffic Control System, Brochure No. TC-21XX–8/08–250, TransCore, 2008.

Sims, A.G. and K.W. Dobinson, "The Sydney Coordinated Adaptive Traffic (SCAT) System Philosophy and Benefits," *IEEE Transactions on Vehicular Technology,* Vol. 29, No. 2, May 1980, pp. 130–137.

Sims, A.G. and A.B. Finlay, "SCATS. Splits and Offsets Simplified (S. O. S.)," *Proceedings of the Australian Road Research Board Conference,* Hobart, Tasmania, Australia, Vol. 12, No. 4, Aug. 27–31, 1984, pp. 17–33.

Stevanovic, A., C. Kergaye, and P.T. Martin, "Field Evaluation of SCATS Traffic Control in Park City, UT," presented at 15th World Congress on ITS, New York City, N.Y., Nov. 16–20, 2008, 12 pp.

Taylor, L., P.R. Lowrie, and S. Greene, *Integrated Corridor Traffic Management: The First Step to Freeway and Arterial Integration,* ITS America, June 1996.

Taylor, W.C. and B. Wilshon, *A Before and After Study of Delay at Selected Intersections in South Lyon* (*Field Study Results*), NTL Record ID 28324, Intelligent Transportation Systems Joint Program Office, Federal Highway Administration, Washington, D.C., 1998, 34 pp.

Wilson, C., G. Millar, and R. Tudge, "Microsimulation Evaluation of the Benefits of SCATS Coordinated Traffic Control Signals," *Proceedings of 85th TRB Annual Meeting,* Paper No. 06-1984, Washington, D.C., Jan. 22–26, 2006, 13 pp.

SCOOT

Bretherton, R.D. and G.T. Bowen, "Recent Enhancements to SCOOT—SCOOT Version 2.4," *Proceedings for the 3rd IEE International Conference on Road Traffic Control,* London, U.K., 1990, pp. 95–98.

Bretherton, R.D., "Current Development in SCOOT: Version 3," *Transportation Research Record 1554,* Transportation Research Board, National Research Council, Washington, D.C., 1996, pp. 48–52.

Bretherton, R.D., K. Wood, and G.T. Bowen, "SCOOT Version 4," *Traffic Engineering and Control,* Vol. 39, No. 7, 1998, pp. 425–427.

Chilukuri, B.R., J. Perrin, Jr., and P.T. Martin, "SCOOT and Incidents: A Performance Evaluation in a Simulated Environment," *Journal of the Transportation Research Board,* Washington, D.C., Jan. 11–15, 2004, pp. 224–232.

Clarke, R., "SCOOT," presented at the 80th Annual Meeting of the Transportation Research Board, Adaptive Traffic Signal Control Workshop, Washington, D.C., Jan. 7, 2001.

Condie, H., et al., *Comparative Evaluation Results and Cost Benefit Analysis—Signal Management in Real Time for Urban Traffic NETworkS,* Deliverable 21, SMART NETS IST-2000-28090 Report for the IST Office, Brussels, Belgium, Mar. 2004.

Day, I., "SCOOT—Split, Cycle & Offset Optimization Technique," presented at the TRB Mid-Year Meeting, Adaptive Traffic Signal Control Workshop, Seattle, Wash., July 12–14, 1998.

El-Assar, H., "Orange County SCOOT System," presented at the 83rd Annual Meeting of the Transportation Research Board, Adaptive Traffic Signal Control Workshop, Washington, D.C., Jan. 11, 2004.

Feng, Y., J. Perrin, Jr., and P.T. Martin, "Bus Priority of SCOOT Evaluated in a VISSIM Simulation Environment," Preprint CD-ROM, prepared for the 82nd Annual Meeting of the Transportation Research Board, Washington, D.C., Jan. 12–16, 2003.

Hansen, B.G., P.T. Martin, and H.J. Perrin, "SCOOT Real-time Adaptive Control in a CORSIM Simulation Environment," *Journal of the Transportation Research Board,* Washington, D.C., Jan. 9–13, 2000, 16 pp.

Hunt, P.B., D.I. Robertson, R.D. Bretherton, and R.I. Winton, "SCOOT—A Traffic Responsive Method of Coordinating Signals," *Report TRRL 1014,* Transport and Road Research Laboratory, Crowthorne, Berkshire, U.K., 1981, 44 pp.

Hunt, P.B., D.I. Robertson, R.D. Bretherton, and M.C. Royle, "The SCOOT On-line Traffic Signal Optimisation Technique," *Proceedings of the International Conference on Road Traffic Signalling,* Institution of Electrical Engineers, London, U.K., Mar. 30/Apr. 1, 1982, pp. 59–62.

Hunt, P.B. and T.R. Holland, "The Effect of an Incident in a SCOOT System—In Simulation and On-Street," *Traffic Engineering & Control,* Vol. 26, No. 2, Feb. 1985, pp. 55–58.

Jansuwan, S. and S. Narupiti, "Assessment of Area Traffic Control System in Bangkok by the Microscopic Simulation Model," *Proceedings of the Eastern Asia Society for Transportation Studies,* Vol. 5, Bangkok, Thailand, 2005, pp. 1367–1378.

Jayakrishan, R., S.P. Mattingly, and M.G. McNally, *Performance Study of SCOOT Traffic Control System with Non-Ideal Detectorization: Field Operational Test in the City of Anaheim,* Report UCI-ITS-WP-00-27, Institute of Transportation Studies, University of California, Irvine, Calif., Dec. 2000.

Jhaveri, C.S., J. Perrin, Jr., and P.T. Martin, "SCOOT Adaptive Signal Control: An Evaluation of its Effectiveness over a Range of Congestion Intensities," *Proceedings of the 82nd Annual Meeting of the Transportation Research Board,* Washington, D.C., Jan. 12–16, 2003.

Jhaveri, C.S., J. Perrin, Jr., and P.T. Martin, "Effectiveness of SCOOT Adaptive Control on Networks and Corridors," *Proceedings of the 83rd Annual Meeting of the Transportation Research Board,* Washington, D.C., Jan. 11–15, 2004.

Kelman, L. and S. Kemp, "Operational Experience with Adaptive Control Systems," presented at the 80th Annual Meeting of the Transportation Research Board, Adaptive Traffic Signal Control Workshop, Washington, D.C., Jan. 7–11, 2001.

Kelman, L., "Traffic Management Measures of Effectiveness," presented at the 80th Annual Meeting of the Transportation Research Board, Adaptive Traffic Signal Control Workshop, Washington, D.C., Jan. 7–11, 2001.

Kergaye, C., A. Stevanovic, and P.T. Martin, "An Evaluation of SCOOT and SCATS Through Microsimulation," *Proceedings of the International Conference on Application of Advanced Technologies in Transportation,* ASCE Transportation and Development Institute, Athens, Greece, May 2008.

Klein, L.A., "Interconnected Intersection Control Using Online-Generated Timing Plans," *Sensor Technologies and Data Requirements for ITS,* Artech House, Norwood, Mass., pp. 98–133, 2001.

Kosonen, I. and A. Bargiela, "Simulation Based Traffic Information System," *Proceedings of the 7th World Congress on ITS,* Turin, Italy, Nov. 6–9, 2000, 8 pp.

Lialias, J.A., "AUSCI GOES SOLO: Advanced Video Detection for Minneapolis," *Traffic Technology International,* Dec. '97/ Jan. '98, pp. 36–38.

Martin, P.T., "SCOOT, an Overview," presented at the 80th Annual Meeting of the Transportation Research Board, Adaptive Signal Control Workshop, Washington, D.C., Jan. 7–11, 2001.

Maxwell, A., "Optimization and Evaluation of Traffic Signal Control in the UK," presented at the 2nd Shanghai (Nepoch-FORUM8) Conference, Shanghai, China, Mar. 12, 2008.

Mazzamatti, M.V., D.V.V.F. Netto, L.M. Vilanova, and S.H. Ming, "Benefits Gained by Responsive and Traffic Adaptive Systems in Sao Paulo," *Proceedings of the International Conference on Road Transport Information and Control,* Institution of Electrical Engineers, London, U.K., 1998, pp. 114–118.

McNally, M.G., et al., "Institutional Evaluation of the Anaheim Adaptive Control Field Operational Test," presented at the PATH Program-Wide Research Meeting, Richmond Field Station, University of California, Berkeley, Nov. 5–7, 1998.

McNally, M.G., J.E. Moore, C.A. MacCarley, and R. Jayakrishan, *Evaluation of the Anaheim Advanced Traffic Control System Field Operational Test: Final Report Task B: Assessment of Institutional Issues,* California PATH Research Report UCB-ITS-PRR-99-27, 1999, 109 pp.

National Transportation Operations Coalition Traffic Signal Action Team, *Assessment of City of Minneapolis, Traffic Signal Management and Operations Program,* Minneapolis, Minn., Feb. 2004, 39 pp.

Ragsdale, P., "AUSCI-SCOOT: A Transatlantic Partnership for Minneapolis," *Traffic Technology International,* Dec. 97/ Jan. 98, pp. 40–42.

Rakha, H. and M. Van Aerde, "REALTRAN: An Off-Line Emulator for Estimating the Impacts of SCOOT," *Transportation Research Record 1494,* Transportation Research Board, National Research Council, Washington, D C., 1995, pp. 124–128.

Reissnecker, A., "SCOOT: Part 2—Equipment Requirements for Adaptive Traffic Control," presented at the 79th Transportation Research Board Annual Meeting, Adaptive Traffic Signal Control Workshop, Washington, D.C., Jan. 9, 2000.

Reynolds, S. and M. Bell, "Quantifying Changes in Carbon Monoxide Levels Following the Installation of SCOOT," *Proceedings of the International Conference on Road Transport Information and Control,* Apr. 21–23, 1998, pp. 40–44.

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

Siemens Traffic Controls Ltd., "SCOOT, Part 1," presented at the 79th Annual Meeting of the Transportation Research Board, Traffic Adaptive Signal Control Workshop, Washington, D.C., Jan. 9, 2000.

Silcock, J.P. and D.A. Crosta, "SCOOT Control of a Simulated Road Network," *Proceedings of the International Conference on Applications of Advanced Technologies in Transportation Engineering,* Capri, Italy, June 27–30, 1995, pp. 583–587.

SRF Consulting Group, *AUSCI Adaptive Urban Signal Control and Integration,* Report SRF No. 0942089.8, Minnesota Department of Transportation, St. Paul, Oct. 2000, 205 pp.

Stevanovic A.Z. and P.T. Martin, "SCOOT and Coordinated Actuated Traffic Control Evaluated through Microsimulation," *Transportation Research Record: Journal of the Transportation Research Board, No. 2080,* Transportation Research Board of the National Academies, 2008, pp. 48–56.

Stevanovic, A., C. Kergaye, and P.T. Martin, "SCOOT and SCATS: A Closer Look into Their Operations," 09-1672, *Proceedings of the 88th Annual Meeting of the Transportation Research Board,* Washington, D.C., Jan. 11–15, 2009.

Taale, H., W.C.M. Fransen, and J. Dibbits, "The Second Assessment of the SCOOT System in Nijmegen," In *Proceedings of the IEE Road Transportation Information and Control Conference,* Publication No. 454. London, U.K., Apr. 21–23, 1998.

Tate, J.E. and M.C. Bell, "Evaluation of a Traffic Demand Management Strategy to Improve Air in Quality Urban Areas," No. 472, *Proceedings of the 10th International Conference on Road Transport Information and Control,* Institution of Electrical Engineers, London, U.K., 2000, pp. 158–162.

Thomas, G., S. Howard, and K. Baffour, "Linkage of Microsimulation Models with UTMC," Paper No. 1047, *Proceedings of the 13th World Congress on ITS,* London, Oct. 8–12, 2006, 8 pp.

Wood, K., "Traffic Restraint by SCOOT Gating," *Urban Transport and the Environment for the 21st Century,* Vol. 18, 1995, pp. 335–342.

Yin, S., Z. Li, and Y. Zhang, "Integrated Traffic Signal Control and Management Platform and its Application," Paper No. 10352, *Proceedings of the 15th World Congress on Intelligent Transport Systems,* New York City, N.Y., Nov. 16–20, 2008, 8 pp.

UTOPIA SPOT

Donati, F., V. Mauro, G., Roncolini, and M. Vallauri, "A Hierarchical Decentralised Traffic Light Control System," *Proceedings from IFAC 9th World Congress,* Vol. II, 11G/A-1, 1984.

Mauro, V. and C. DiTaranto, "UTOPIA," Control, Computers, Communications in Transportation: Selected Papers from the IFAC Symposium, 1990, pp. 245–252.

Mauro, V., "UTOPIA—Urban Traffic Control—Main Concepts," presented at the EU–China ITS Workshop, Beijing, China, Apr. 18–19, 2002.

Pesti, G., P.S. Byrd, M. Kruse, and P.T. McCoy, *Evaluation of the SPOT Adaptive Traffic Control System,* FHWA Technology Project No. 97068, Federal Highway Administration, Nebraska Department of Roads, Omaha, May 1999, 35 pp.

Turksma, S. and J. Vreeswijk, "Fuel Efficiency in Cooperative Network Control Systems," *Proceedings of the 15th World Congress on ITS,* Paper No. 20106, New York City, N.Y., Nov. 16–20, 2008, 7 pp.

MISCELLANEOUS ATCSS

Abdulhai, B., R. Pringle, and G.J. Karakoulas, "Reinforcement Learning for True Adaptive Traffic Signal Control," *Journal of Transportation Engineering,* Vol. 129, No. 3, May/June 2003, pp. 278–285.

Abu.-Lebdeh, G., "Integrated Adaptive-Signal Dynamic-Speed Control of Signalized Arterials," *Journal of Transportation Engineering,* Vol. 128, No. 5, Sep./Oct. 2002, pp. 447–451.

Aguigui, K.G. and T. Hong, "A Demonstration Adaptive Signal System: The San Francisco Bay Area Experience," *Proceedings of the 10th World Congress on ITS,* Madrid, Spain, Nov. 16–20, 2003, 11 pp.

Athmaraman, N. and S. Soundararajan, "Adaptive Predictive Traffic Timer Control Algorithm," *Proceedings of the 2005 Mid-Continent Transportation Research Symposium,* Ames, Iowa, Aug. 2005, 10 pp.

Barcelo, J., R. Grau, and S. Benedito, "Cars: A Demand-Responsive Traffic Control System," *Proceedings of the 2nd International Conference on Applications of Advanced Technologies in Transportation Engineering,* Minneapolis, Minn., Aug. 18–21, 1991, pp. 91–95.

Boillot, F., J.M. Blosseville, J.B. Lesort, V. Motyka, M. Papageorgiou, and S. Sellam, "Optimal Signal Control of Urban Traffic Networks," *Proceedings of the IEE Conference on Road Traffic Monitoring,* IEE Conference Publication No. 355, 1992, pp. 75–79.

Boillot, F., S. Midenet, and J.C. Pierrelee, "The Real-time Urban Traffic Control System CRONOS: Algorithm and Experiments," *Transportation Research Part C: Emerging Technologies,* Vol. 14, No. 1, Feb. 2006, pp. 18–38.

Cheng, S.F., M.A. Epelman, and R.L. Smith, "CoSIGN: A Parallel Algorithm for Coordinated Traffic Signal Control," *IEEE Transactions on Intelligent Transportation Systems,* Vol. 7, No. 4, Dec. 2006, pp. 551–564.

Chen, W., L. Chen, Z. Chen, and S. Tu, "A Realtime Dynamic Traffic Control System Based on Wireless Sensor Network," *Proceedings of the International Conference on Parallel Processing Workshops,* IEEE Computer Society, Washington, D.C., 2005, pp. 258–264.

Chin, D.C. and R.H. Smith, "A Traffic Simulation for Mid-Manhattan with Model-Free Adaptive Signal Control," *Proceedings of the 1994 Summer Computer Simulation Conference,* San Diego, Calif., July 18–20, 1994, pp. 296–301.

Condie, H., et al., *Comparative Evaluation Results and Cost Benefit Analysis—Signal Management in Real Time for Urban Traffic NETworkS,* Deliverable 21, SMART NETS IST-2000-28090 Report for the IST Office, Brussels, Belgium, Mar. 2004.

Dotoli, M., M.P. Fanti, and C. Meloni, "A Signal Timing Plan Formulation for Urban Traffic Control," *Control Engineering Practice,* Vol. 14, No. 11, Nov. 2006, pp. 1297–1311.

Fehon, K., R. Chong, and J. Black, "Adaptive Traffic Signal System for Cupertino California," *Proceedings of the 4th Asia–Pacific Transportation Development Conference,* 16th Annual Meeting of ICTPA, Apr. 18–20, 2003, 14 pp.

Friedrich, B., "Adaptive Signal Control: An Overview," *Proceedings of the 9th Meeting of the Euro Working Group Transportation,* Polytechnic University of Bari, Bari, Italy, June 10–12, 2002, pp. 571–574.

Guan, D. and Z. Yang, "Signal Timing Optimization for Urban Traffic Adaptive Control System," *Proceedings of the International Conference on Traffic & Transportation Studies 2002,* Guilin, China, July 23–25, 2002, pp. 871–876.

Henry, J.J., J.L. Farges, and J. Tufal, "The PRODYN Real Time Traffic Algorithm," *Proceedings of the IFAC Symposium,* Baden–Baden, Germany, 1983.

Henry, J.J., "PRODYN Tests and Future Experiments on ZELT," *Proceedings of the Vehicle Navigation and Information Systems Conference,* Toronto, ON, Canada, Sep. 11–13, 1989, pp. 292–295.

Heydecker, B.G., "Objectives, Stimulus, and Feedback in Signal Control of Road Traffic," *Journal of Intelligent Transportation Systems: Technology, Planning, and Operations,* Vol. 8, No. 2, Apr. 1, 2004, pp. 63–76.

Hunter, M. and R.B. Machemehl, *Development and Validation of a Flexible, Open Architecture, Transportation Simulation with an Adaptive Control Implementation,* Report SWUTC/04/167823-1, Center for Transportation Research University of Texas, Austin, June 2004, 276 pp.

"ITACA. Intelligent Traffic Lights—Easing Traffic Congestion in Sao Paulo," Telvent, Spain, Aug. 21, 2003, 2 pp. [Online]. Available: http://www.idatahouse.com/customers/case_studies/traffic/ITACASaoPauloCase Study.pdf.

Khashashina, R., Z. Yang, and R. Martinez, "New York City's Advanced Transportation Controller Program: Design and Project Management Challenges," *Proceedings of the 15th World Congress on ITS,* New York City, N.Y., Nov. 16–20, 2008, 9 pp.

Kosmatopoulos, E., M. Papageorgiou, C. Bielefeldt, V. Dinopoulou, R. Morris, J. Mueck, A. Richards, and F. Weichenmeier, "International Comparative Field Evaluation of a Traffic-Responsive Signal Control Strategy in Three Cities," *Transportation Research Part A,* Vol. 40, 2006, pp. 399–413.

Lam, J.K., C. Perry, and K. Lee, "Future Challenges in Traffic Control," *Proceedings of the 15th World Congress on ITS,* New York City, N.Y., Nov. 16–20, 2008, 8 pp.

Pesti, G., P.S. Byrd, M. Kruse, and P.T. McCoy, *Demonstration of State-of-the-Art Integrated Traffic Management System,* Report FHWA 97068, Department of Civil Engineering, University of Nebraska, Lincoln, May 1999.

Pleydell, M. and M. Wylie, "Millbrook—An Example of Joined up Control and Modelling," *Proceedings of the 15th World Congress on ITS,* New York City, N.Y., Nov. 16–20, 2008, 7 pp.

Sen, S. and K.L. Head, "Controlled Optimization of Phases at an Intersection," *Transportation Science,* Vol. 31, No. 1, Feb. 1997, pp. 5–17.

Shenoda, M. and R. Machemehl, Development of a Phase-by-Phase, Arrival-Based, Delay-Optimized Adaptive Traffic Signal Control Methodology with Metaheuristic Search, Report SWUTC/06/167863-1, Center for Transportation Research University of Texas, Austin, Oct. 2006, 102 pp.

Srinivasan, D., C.C. Min, and R.L. Cheu, "Neural Networks for Real-Time Traffic Signal Control," *IEEE Transactions on*

Intelligent Transportation Systems, Vol. 7, No. 3, Sep. 2006, pp. 261–272.

Talas, M., "ITS and Traffic Control Strategies in New York City," *Proceedings of the 15th World Congress on ITS,* New York City, N.Y., Nov. 16–20, 2008, 13 pp.

TEI Engineers & Planners, Evaluation of Deployment Strategies Pinellas Countywide ATMS/Adaptive Control Implementation Project, Pinellas County Metropolitan Planning Organization, Clearwater, Fla., June 4, 2003, 19 pp.

Tomlinson, A. and L. Bull, *Towards Distributed Adaptive Control for Road Traffic Junction Signals using Learning Classifier Systems,* Report UWELCSG02-004, University of the West of England, Bristol, U.K., 2004, 21 pp.

Vogiatzis, N., H. Ikeda, and W. Wibisono, "On the Locality-Scope Model for Improving the Performance of Transportation Management Systems," *Road and Transport Research,* Vol. 14, No. 2, June 2005, pp. 72–83.

Weng, X.X., S.S. Yao, and X.F. Zhu, "Architecture of Multi-agent System for Traffic Signal Control," *Proceedings of the 8th International Conference on Control, Automation, Robotics and Vision,* Kunming, China, 2004, pp. 2199–2204.

Wey, W.-M. and R. Jayakrishnan, "Performance Studies of a Network Adaptive Traffic Control Algorithm via Simulation Model," *Proceedings of the IEEE Conference on Intelligent Transportation Systems,* 2001, pp. 663–668.

Xin, W., W.R. McShane, S. Muthuswamy, and J. Chang, "An Integrated Real-time Decision Support System for Adaptive Signal Control," *Proceedings of the 15th World Congress on ITS,* New York City, N.Y., Nov. 16–20, 2008, 9 pp.

Yu, T., *On-line Traffic Signalization using Robust Feedback Control,* Ph.D. dissertation, Virginia Polytechnic Institute and State University, Blacksburg, Dec. 18, 1997.

Yu, X.H. and W.W. Recker, "Stochastic Adaptive Control Model for Traffic Signal Systems," *Transportation Research Part C: Emerging Technologies,* Vol. 14, No. 4, Aug. 2006, pp. 263–282.

DEPLOYMENT REPORTS ON ATCS

Dey, D.W., S. Fitzsimons, A. Morris, and D. Ng, "Adaptive Traffic Signal Interconnect in Menlo Park and Sunnyvale, CA," *Proceedings of the ITE District 2004 Annual Meeting,* Sacramento, Calif., 2004, 13 pp.

"Intelligent Transportation Systems (ITS), Advisory Committee Meeting Minutes, October 16, 2002," 6 pp. [Online]. Available: http://www.pinellascounty.org/mpo/ITS/agendas/10_16_02.pdf.

Intelligent Transportation Systems (*ITS*) *Projects Book,* Report EDL#13631, U.S. Department of Transportation Intelligent Transportation Systems (ITS) Joint Program Office, Federal Highway Administration, Federal Transit Administration, and National Highway Traffic Safety Administration, Washington, D.C., 2002, 584 pp.

Kennedy, L., *Council Meeting Synopsis,* City Council Summary 12.17.07, City Clerk's Office, City of Alpharetta, Ga, Dec. 18, 2007.

Midwest Research Institute, *Adaptive Signal Timing Research Along Route 291 in Kansas City, Missouri,* Report for MRI Project 110637, June 2009, 77 pp.

Tindale–Oliver & Associates, Inc., *Martin County Advanced Traffic Management Systems* (*ATMS*) *Assessment,* Report 181011-02.07, Oct. 29, 2007, 81 pp.

GENERAL PRESENTATIONS ON ATCS

Dolan, F.L., "Adaptive Traffic Signal Systems Detectors & Communication Devices," presented at the TRB Annual Signal Systems Committee Meeting, Adaptive Signal Control Systems Workshop, Washington, D.C., Jan. 7, 2001.

Eyler, D., "Traffic Responsive Signal Coordination," presented at the TRB Midyear Signal Systems Committee Meeting, Toronto, ON, Canada, July 25–27, 2004.

Fehon, K., "North American Development of Adaptive Traffic Signal Systems," *Proceedings of the ITE 2005 Annual Meeting and Exhibit Compendium of Technical Papers,* Melbourne, Australia, Aug. 5–7, 2005, 17 pp.

Grayson, G.E., "Available Adaptive TCS Offerings," presented at the Adaptive Traffic Control Workshop, Oakland, Calif., Nov. 14, 2007.

Hicks, B. and M. Carter, "What Have We Learned about ITS Arterial Management?" In *What Have We Learned About Intelligent Transportation Systems?* Federal Highway Administration, Washington, D.C., Dec. 2000, pp. 45–63.

Lam, J., "State of the Art in Adaptive Traffic Control," presented at the ITS Canada 4th Annual Conference and General Meeting, Vancouver, BC, Canada, Mar. 11–13, 2001.

Martin, P.T., "Traffic Adaptive Signal Control Systems Myth and Reality," presented at the ITE 36th Annual Meeting of the Inter-Mountain and Colorado–Wyoming Sections Chapter, Jackson Hole, Wyo., May 17–18, 1996.

Pearson, R., *Traffic Signal Control,* ITS Decision Report, 2000 [Online]. Available: http://www.path.berkeley.edu/itsdecision/serv_and_tech/Traffic_signal_control/trafficsig_report.html.

Raamot, E., "Discussion of Tools, Techniques, and the Implementation of the Intelligent Signal Systems," presented at the ITS Adaptive Traffic Control Workshop, Oakland, Calif., Nov. 14, 2007.

Schroeder, M., *State-of-the-Art Review of Adaptive Arterial Control Systems,* Research Project GC 8286, Task 30, Arterial Control and Integration, Washington State Transportation Center, Olympia, June 1989.

Urbanik, T., "Traffic Management Policies," presented at the TRB Annual Signal Systems Committee Meeting, Adaptive Signal Control Systems Workshop, Washington, D.C., Jan. 7, 2001.

"Urban Traffic Control Systems," edited at the Institute for Transport Studies, University of Leeds, Leeds, U.K. [Online]. Available: http://www.konsult.leeds.ac.uk/private/level2/instruments/instrument014/l2_014a.htm.

GOVERNMENT REPORTS ON ATCS

Gordon, R.L., *NCHRP Synthesis 307: Systems Engineering Processes for Developing Traffic Signal Systems,* Transportation Research Board, National Research Council, Washington, D.C., 2003, 87 pp.

Gordon, R.L. and W. Tighe, *Traffic Control Systems Handbook,* Report FHWA-HOP-06-006, Office of Transportation Management, Federal Highway Administration, Washington, D.C., Oct. 2005, 367 pp.

Klein, L.A., M.K. Mills, and D.R.P. Gibson, *Traffic Detector Handbook: Third Edition—Volume I,* Report FHWA-HRT-06-108, Federal Highway Administration, Washington, D.C., Oct. 2006, 291 pp.

Malek, S., R. Denney, and J.A. Halkias, "Traffic Signal Control Systems," In *Advanced Transportation Management Technologies Participant Notebook,* Report FHWA-SA-97-060, Federal Highway Administration, Washington, D.C., 1997, pp. 3.1–3.15.

PREVIOUS SURVEYS ON ATCS

Crenshaw, P., "FHWA Adaptive Control Survey," presented at the TRB A3A18 Meeting, 2000 Midyear Meeting Minutes, Seattle, Wash., July 9–10, 2000.

Martin, P.T., "Adaptive Control Systems Survey," presented at the 83rd Annual Meeting of the Transportation Research Board, Signal Control Priority for Transit and Adaptive Signal Control Workshop, Washington, D.C., Jan. 11–15, 2004.

Martin, P.T. and R. Disegni, *TRB Traffic Signals Committee, Adaptive Traffic Signals Control Systems Survey,* Report UTL-(07/02)-(57), University of Utah, Salt Lake City, Aug. 2002, 54 pp.

"Workshop on Adaptive Signal Control Systems—TRB 2001," presented at the TRB Traffic Signal Systems Committee—A3A18, Washington, D.C., 2001 [Online]. Available: http://www.signalsystems.org.vt.edu/documents/Jan2001AnnualMeeting/AdaptiveWorkshopMap_TRB2001.pdf.

THEORETICAL STUDIES ON ATCSS

Abdulhai, B., R. Pringle, and G.J. Karakoulas, "Reinforcement Learning for True Adaptive Traffic Signal Control," *Journal of Transportation Engineering,* Vol. 129, No. 3, May/June 2003, pp. 278–285.

Abdulhai, B. and L. Kattan, "Reinforcement Learning: Introduction to Theory and Potential for Transport Applications," *Canadian Journal of Civil Engineering,* Vol. 30, No. 6, Dec. 2003, pp. 981–991.

Abu-Lebdeh, G., "Integrated Adaptive-Signal Dynamic-Speed Control of Signalized Arterials," *Journal of Transportation Engineering,* Vol. 128, No. 5, Sep./Oct. 2002, pp. 447–451.

Athmaraman, N. and S. Soundararajan, "Adaptive Predictive Traffic Timer Control Algorithm," *Proceedings of the 2005 Mid-Continent Transportation Research Symposium,* Ames, Iowa, Aug. 2005, 10 pp.

Burton, R. and N. Hounsell, "Bus Priority and UTC Systems: The PROMPT Project," *Proceedings of the IEE Vehicle Navigation & Information Systems Conference,* Ottawa, ON, Canada, Oct. 12–15, 1993, pp. 602–605.

Camponogara, E., S. Galvao de Souza, and W. Kraus, "A Mathematical Programming Model for Urban Traffic Control," *Proceedings of the 13th Pan-American Conference of Traffic and Transportation Engineering,* Albany, N.Y., Sep. 2004, 12 pp.

Chin, D.C. and R.H. Smith, "A Traffic Simulation for Mid–Manhattan with Model-Free Adaptive Signal Control," *Proceedings of the 26th Annual Summer Computer Simulation Conference,* 1994, pp. 296–301.

Deng, L.Y., N.C. Tang, D. Lee, C.T. Wang, and M.C. Lu, "Vision Based Adaptive Traffic Signal Control System Development," *Proceedings of the 19th International Conference on Advanced Information Networking and Applications,* Vol. 2, 2005, pp. 385–388.

Diakaki, C., M. Papageorgiou, and K. Aboudolas, "A Multivariable Regulator Approach to Traffic-Responsive Network-Wide Signal Control," *Control Engineering Practice,* Vol. 10, 2002, pp. 183–195.

Fang, F.C. and L. Elefteriadou, "Development of an Optimization Methodology for Adaptive Traffic Signal Control at Diamond Interchanges," *Journal of Transportation Engineering,* Vol. 132, No. 8, Aug. 2006, pp. 629–637.

Heydecker, B.G., "Objectives, Stimulus and Feedback in Signal Control of Road Traffic," *Journal of Intelligent Transportation Systems: Technology, Planning, and Operations,* Vol. 8, No. 2, Apr. 1, 2004, pp. 63–76.

Kwon, E. and Y.J. Stephanedes, "Development of an Adaptive Control Strategy in a Live Intersection Laboratory," *Transportation Research Record 1634,* Transportation Research Board, National Research Council, Washington, D.C., 1998, pp. 123–129.

Lange, J. and J. Wahle, "Quality Control in Urban Traffic Control," *Proceedings of the 5th World Congress on ITS,* Seoul, South Korea, 1999.

Li, H. and P.D. Prevedouros, "Traffic Adaptive Control for Oversaturated Isolated Intersections: Model Development and Simulation Testing," *Journal of Transportation Engineering,* Vol. 130, No. 5, Sep./Oct. 2004, pp. 594–601.

List, G.F. and M. Cetin, "Modeling Traffic Signal Control Using Petri Nets," *IEEE Transactions on Intelligent Transportation Systems,* Vol. 5, No. 3, Sep. 2004, pp. 177–187.

Mertz, J., F. Weichenmeier, and T. Schon, "A Combined Adaptive/Fuzzy Network-Control and its Application within the Munich Open System Architecture," *Proceedings of the IEEE Conference on Intelligent Transportation Systems,* Oakland, Calif., Aug. 25–29, 2001, pp. 45–49.

Mirchandani, P.B. and N. Zou, "Queueing Models Revisited: Analysis of Vehicular Delays and Queues using Adaptive Control at Intersections and Ramps," presented at the Sixth Triennial Symposium on Transportation Analysis, Phuket Island, Thailand, June 10–15, 2007, 3 pp.

Mikhailov, L. and R. Hanus, "Hierarchical Control of Congested Urban Traffic—Mathematical Modelling and Simulation," *Mathematics and Computers in Simulation,* Vol. 37, No. 2–3, Nov. 30, 1994, pp. 183–188.

Ozbay, K., et al., *Evaluation of Adaptive Control Strategies for NJ Highways,* Report FHWA-NJ-2006-001, New Jersey Department of Transportation, Trenton, Jan. 2006, 253 pp.

Paksarsawan, S., A.D. May, and F.O. Montgomery, "The Simulation of Variable Traffic Signal Control in the Bangkok Network," *Transportation Planning and Technology,* Vol. 22, No. 4, 1999, pp. 287–308.

Ruimin, L., L. Jiangang, and L. Huapu, "Multi-layer Traffic Signal Control Model Based on Fuzzy Control and Genetic Algorithm," *Proceedings of the 9th International Conference on Applications of Advanced Technology in Transportation,* Chicago, Ill., Aug. 13–16, 2006, pp. 461–466.

Saiyed, S. and J.A. Stewart, "An Assessment of Pre-timed, Actuated and Adaptive Signal Control Strategies for Unsaturated and Saturated Arterial Network," ITE 2005 Annual Meeting and Compendium of Technical Papers, ITE, Washington, D.C., 2004, 15 pp.

Shoufeng, L., L. Ximin, and D. Shiqiang, "Q-Learning for Adaptive Traffic Signal Control Based on Delay Minimization Strategy," *Proceedings of IEEE International Conference on Networking, Sensing and Control,* Sanya, China, 2008, pp. 687–691.

Smith, R.H. and D.C. Chin, "Evaluation of an Adaptive Traffic Control Technique with Underlying System Changes," *Proceedings of the Winter Simulation Conference,* Arlington, Va., Dec. 3–6, 1995, pp. 1124–1130.

Spall, J.C. and D.C. Chin, "Traffic-Responsive Signal Timing for System-Wide Traffic Control," *Transportation Research Part C: Emerging Technologies,* Vol. 5, No. 3–4, June–Aug, 1997, pp. 153–163.

Van Katwijk, R.T., P. Van Koningsbruggen, B. De Schutter, and J. Hellendoorn, "Test Bed for Multiagent Control Systems in Road Traffic Management," *Transportation Research*

Record: Journal of the Transportation Research Board, No. 1910, Transportation Research Board of the National Academies, Washington, D.C., 2005, pp. 108–115.

Van Katwijk, R.T., B. De Schutter, and J. Hellendoorn, "Traffic Adaptive Control of a Single Intersection: A Taxonomy of Approaches," *Proceedings of the 11th IFAC Symposium on Control in Transportation Systems,* Delft, The Netherlands, Aug. 29–31, 2006, pp. 227–232.

Van Katwijk, R.T., B. De Schutter, and J. Hellendoorn, "Lookahead Traffic Adaptive Control of a Single Intersection—A Taxonomy and a New Hybrid Algorithm," *Proceedings of the 9th TRAIL Congress 2006—TRAIL in Motion—CD-ROM,* Rotterdam, The Netherlands, Nov. 2006, 14 pp.

Van Zuylen, H.J. and H. Taale, "Anticipatory Optimization of Traffic Control," *Transportation Research Record: Journal of the Transportation Research Board, No. 1725,* Transportation Research Board, National Research Council, Washington, D.C., 2000, pp. 109–115.

Yang, N. and Y. Liu, "Simulation Optimization of Urban Arterial Signals via Simultaneous Perturbation Stochastic Approximation (SPSA)," *Proceedings of the 15th World Congress on ITS,* New York City, N.Y., Nov. 16–20, 2008, 10 pp.

Yu, X.-H. and W.W. Recker, "Stochastic Adaptive Control Model for Traffic Signal Systems," *Transportation Research Part C: Emerging Technologies,* Vol. 14, No. 4, Aug. 2006, pp. 263–282.

Zheng, X., W. Recker, and L. Chu, "Optimization of Control Parameters for Adaptive Traffic-Actuated Signal Control," *Proceedings of the 15th World Congress on Intelligent Transport Systems,* Paper No. 30443, New York City, N.Y., Nov. 16–20, 2008, 12 pp.

Zhou, G., A. Gan, and D. Lue, "Application of Parallel Genetic Algorithm (PGA) in Adaptive Traffic Signal Timing Optimization," *Proceedings of the 15th World Congress on Intelligent Transport Systems,* Paper No. 30263, New York City, N.Y., Nov. 16–20, 2008, 12 pp.

Abbreviations used without definitions 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
HMCRP	Hazardous Materials Cooperative Research Program
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
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-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