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Traffic Signal Systems
Addressing Diverse Technologies and Complex User Needs

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In the next millennium, traffic signal systems will need to address many issues, spanning a broad range of technical, social, and political boundaries. With the increase in urbanization and traffic congestion comes a greater demand to operate our roadway systems with maximum efficiency. As traffic volume continues to increase, roadway capacity will increase at a slower rate. New technology, such as traffic-responsive closed-loop systems or adaptive traffic signal systems using advanced surveillance and traffic management centers, will become increasingly critical for city, county, and state organizations to meet transportation needs. Such systems depend heavily on field infrastructures such as vehicle detection, distributed microprocessor-based control systems, and near real-time interaction over diverse communication media. It is critical to have all of these elements operating in a stable, well-maintained environment, even during maintenance and construction. This is particularly challenging given the diversity of government agencies often responsible for different portions of what motorists perceive as a single transportation system. Each government agency typically has traffic-signal control technology of varying vintages and different procedures for operating traffic signal systems. Signal system operation is even further complicated by the recent trend that views traffic signal systems as a small component of an integrated multimodal transportation system. When such a perspective is adopted, the “customers” of traffic signal systems are much more diverse than just automobile drivers and require a high degree of agency cooperation.

HISTORICAL PERSPECTIVE

Increasing traffic at intersections within urban areas caused concern for safety and congestion as early as the 1850s. The first attempt at controlling intersection traffic was the development of manually turned semaphores, operated by police officers, in London, England in 1868 (*1*). These devices were first introduced in the United States in 1908 in New York, and their use quickly spread. The electrification of urban areas led to the development and installation of the first electrically operated traffic signal in Cleveland, Ohio in 1914. In 1919, New York, began converting from hand-cranked semaphores to electromechanical controllers. In 1923, Garrett Morgan patented the Morgan traffic signal, which was later sold to General Electric. By 1932, the last hand-cranked semaphore on Parkside Avenue in Brooklyn was replaced by an electromechanical controller.

For nearly 50 years, from the 1920s until the 1970s, the electromechanical controller dominated the traffic signal systems market. Cycle lengths were programmed by installing appropriate gears and the cycle was split into various intervals by inserting pins on a timing dial. To accommodate variations in traffic demands, the concept was extended to provide "three dials." Also, to ensure that adjacent intersections were operating as a "traffic signal system" with predictable cycle lengths, splits, and offsets, a "seven-wire" interconnect procedure was developed so that adjacent electromechanical controllers could work together in a systematic manner (*2*). Even as we reach the millennium, some urban areas have traffic signal systems based on three-dial electromechanical controllers and seven-wire interconnect systems. Furthermore, much of the terminology developed to describe the electromechanical systems is still in use today to describe parameters in modern microprocessor-based controllers.

Subsequent parts of this paper review more recent developments in microprocessor-based traffic signal systems to set the context for anticipated developments in traffic signal systems during the next millennium. While reading these sections, it is instructive to recall George Santayana's famous quote: "Those who cannot remember the past are condemned to repeat it."

Emergence of Microprocessor-Based Traffic Signal Control

During the early 1960s, computers were introduced to traffic signal systems. In 1963, the first computerized traffic signal control system was installed in Toronto, Canada. Developments progressed at a relatively modest pace until the 1970s, when microprocessors became commonly available and hardware and software standardization efforts were first initiated. These efforts attracted a significant following that has profoundly impacted the practices and equipment used today. Each of these developments is described in the following sections.

National Electrical Manufacturers Association Traffic Control Standard

The move by vendors to microprocessor-based controllers was largely motivated by market forces. In contrast to the electromechanical controllers, the microprocessor-based controllers allowed vendors to add new features by changing firmware. The rapid advancement of the microprocessor and intense competition led to many developments (e.g., alternative phase sequences and new detector operating modes) as well as a variety of vendors rapidly entering and exiting the traffic control field. Because competing vendors produced these control devices, each vendor attempted to distinguish its products; as a result, there was not much commonality between controllers manufactured by different vendors. Because many states competitively procured these devices and had a variety of devices from different vendors, this incompatibility led to frustration for maintenance personnel. To address these inconsistencies, a group of vendors came together in the 1980s to draft a standard specification commonly referred to as TS1 (*3*). That specification defined the operation and electrical pins on the A, B, and C connectors for a controller capable of providing isolated actuated control.

The National Electrical Manufacturers Association (NEMA) TS1 standard was based on the philosophy that controllers would provide a basic set of features and standard connectors. Manufacturers would compete based on the hardware and software they provided inside the controllers. The NEMA TS1 standard was successful for isolated actuated intersection control, but it lacked sufficient detail for implementing more advanced features, such as coordinated-actuated operation and preemption. Individual vendors supplemented the standard by providing the complement of features necessary for deploying coordinated-actuated traffic signal systems. This introduced incompatibility and procurement issues, particularly when government agencies needed to upgrade existing signal systems at a later date and had to solicit competitive bids. Nevertheless, the competitive market forces continued to rapidly advance the state of the practice and created a following that led many states to adopt the NEMA standard. In the late 1980s and early 1990s, the NEMA TS1 specification was updated (NEMA TS2) to provide coordinated-actuated operation, preemption, and an optional serial bus that would simplify cabinet wiring (*4*).

Model 170 Specification

In a somewhat parallel track to the NEMA developments, the California Department of Transportation (Caltrans) and the New York Department of Transportation (DOT) developed a specification designed to provide both standard connectors and portable software. The philosophy of this standard was somewhat different from the NEMA standard because it provided a precise specification for a generic traffic control microcomputer. This specification defined microprocessors, memory, input and output addresses, serial ports, mechanical form factor, and electrical connectors. In theory, anyone could develop a Motorola 6800-based program, burn that program onto an EPROM, plug it into a Model 170, and run the software. This allowed the traffic control software (and vendor) to be decoupled from the vendor of the Model 170 controller hardware. Although the standard locked adopting agencies into the computing power of the 1970s, it also was enormously successful because agencies could purchase the controller software and then, at a later date, competitively procure additional Model 170s capable of running the software. One surprising outcome of this approach was only a limited number of software vendors decided to develop and update Model 170 software. As a result, the software vendors were under less competitive market pressures than were the NEMA vendors.

Urban Traffic Control Software

Various agencies around the world have experimented with centralized control of traffic signals. In the 1970s, the Federal Highway Administration (FHWA) embarked on an effort to develop a structured approach to centralized traffic signal control called urban traffic control software (UTCS). UTCS developers defined various levels of control ranging from time of day plan selection to online fully adaptive signal timing. Although the ultimate goal of an online adaptive control system was never realized, the effort resulted in technology that many cities used to implement early computer-controlled signal systems that are still in operation today. Furthermore, many of the traffic operation center concepts and system displays currently used were developed during the deployment of these early UTCS systems.

Increased Interest in Standards

The 1990s began a new direction in traffic signal control, partly as a result of the 1991 Intermodal Surface Transportation Efficiency Act (ISTEA) and partly as the result of rapidly developing computer and communication technology. This stimulated an interest in resolving computer and communication interoperability issues in traffic signal systems. Two significant standardization efforts emerged:

- National Transportation Communications for ITS Protocol (NTCIP); and
- Advanced Transportation Controller (ATC).

The NTCIP effort was targeted at standardizing the communication to traffic signal controllers. The ATC effort was targeted at standardizing the computing platform inside the traffic signal controllers. A renewed interest in real-time adaptive traffic control resulted in prototype development and deployments of various adaptive signal control systems (*5,6*). All of these new initiatives have similarities with hardware and software development efforts during the 1970s.

National Transportation Communication for ITS Protocol

The NTCIP effort was initiated to develop standards and protocols that would allow traffic signal controllers from different vendors to be interoperable in traffic signal systems. As work on the effort unfolded, a variety of communication media, protocol stacks (*7-9*), and data elements were included in the specifications (*10,11*). The resulting TS 3.5 specification is particularly noteworthy for the extensive definitions of common traffic engineering terms. Furthermore, if all data elements defined in NEMA TS 3.5 are implemented by a particular controller vendor, there can be a reasonable level of interchangeability. However, the NTCIP specification for actuated traffic signal controllers is not comprehensive. To prevent compatibility issues from plaguing the NTCIP effort, it will be particularly important for government agencies procuring NTCIP-compliant devices to ensure that important features for closed loop systems coordination, preemption, transit priority, and bicycles are further defined and updated in an orderly fashion as the standard matures.

Advanced Transportation Controller

The concept of an ATC was initiated in 1989. Caltrans prepared a report documenting some of the deficiencies of the Model 170 controller and recommended a 3U VME-based platform using OS-9 (*12*). The concept of the new platform was that traffic signal controllers should not be based on static technology (like the Model170 specification) but on widely used commercial standards, allowing new technology to be adopted rapidly. The initial specification developed by Caltrans was called the Model 2070. Ideally, new technology would be incorporated into the Model 2070 traffic signal controller at a rate similar to that observed in the desktop computing market. As interest in the standard development effort broadened, and more public agencies began participating, an ATC standard emerged that is even less dependent on the processor and operating system than the Model 2070.

CURRENT AND FUTURE MANAGEMENT CHALLENGES

Although the actual traffic signal system technology has evolved significantly during the 20th century, many issues, such as funding, political support, management, training, interjurisdiction coordination, and common regional visions for system operation (*13*), have, significant opportunities for improvement (*14*).

Funding is the major enabling resource that many transportation agencies cite as deficient. In urban areas, traffic engineering departments are often competing for funding with high profile agencies such as police and fire departments, or more tangible capital improvements. When revenue shortfalls occur, elected officials often make the difficult budget decisions that underfund budgets for traffic signal system operation and maintenance. To address this problem, the traffic engineering community needs to develop procedures and methods for accurately quantifying the benefits of well-maintained signal systems (or true costs of poorly maintained signal systems) and then present that information to elected officials in a fair and convincing manner.

Once sufficient funding is obtained, traffic engineers must invest those funds in efforts that generate the biggest return. These efforts typically include:

- Operation and maintenance procedures that define methods for designing signal timing plans, construction standards, maintenance schedules (relamping, conflict monitor testing, etc.), and long-range budgeting for reinvestment in capital infrastructure.
- Personnel training that includes existing practices as well as continuing education in the deployment of emerging technology and the use of equipment that can save money and improve service. Ideally, personnel training should occur at all levels in the organization, reaching technicians, engineers, and management.
- Interjurisdiction coordination of traffic signals so that two or more agencies can work together for the benefit of the public. This often requires that agencies give up some of their autonomy for the benefit of the whole system, raising several issues, such as trust and communication, organizational operating philosophy, control hierarchy, and liability.

It should be pointed out that funding is only an enabling resource. Selecting the proper mix of operation and maintenance, training, and interjurisdictional coordination efforts is not a precise science and will vary by an individual agency's vision for integrated operation of various transportation modes.

CURRENT AND FUTURE TECHNICAL CHALLENGES (RESEARCH ISSUES)

Traffic signal research has been conducted in two distinct areas: roadside equipment and analytical-type operations research. Government agencies and vendors have performed virtually all the research on roadside equipment. Similarly, universities have performed virtually all the research in analytical-type operations. Although significant advancements have been made in both the roadside equipment and analytical models, neither area has been particularly closely coordinated with the other. Many of the following research issues fall outside the typical DOT, commercial, and university organizational structure, but they show considerable promise for improving the operation of traffic signal systems.

System Integration Research

As a result of past research, government agencies and vendors have perfected systems that do an excellent job of meeting today's needs when considered in isolation, but do not provide the building blocks for cost-effectively implementing integrated and interoperable systems manufactured by a variety of vendors. Similarly, many of the promising control algorithms proposed over the years have never been implemented, because many of the assumptions made by the universities developing the models do not reflect the technical limitations or traffic engineering conventions imposed by modern controllers.

Adaptive Control

Recently, FHWA has been attempting to bridge this gap with the development of the real-time traffic adaptive control projects initiated in 1993. Several industry and academic teams emerged to develop new adaptive control systems that have the potential to reduce the effort needed to develop and maintain good traffic signal timings. During this process, various models were proposed and are being deployed. However, the concepts underlying adaptive control are still not mature and there is no consensus on the models. Significantly more effort is needed to understand and resolve the issues differentiating competing approaches. Bringing together the diverse models in a standard architecture is the challenge for streamlining deployment. The deployment will provide a mechanism for comprehensive field evaluations of individual models under alternative traffic patterns and network topologies. It is unlikely that any one approach will provide a universal solution; instead, different models likely will perform better (or worse) on specific network topologies or traffic-flow patterns.

Sensors

Sensors are the eyes and ears of any traffic signal system, yet are viewed by many as the weakest link in developing better traffic control systems. Sensing needs include queue estimation, train detection, nonferrous bicycle detection, emergency vehicle detection, transit vehicle detection, pedestrian detection, vehicle detection, and environmental sensors (weather, air quality). Not only must new sensing technology be developed, but reliability must increase and costs decrease to facilitate widespread use. Furthermore, standards need to emerge for integrating these sensors into traffic signal systems. The standard practice for bringing any sensor information into a traffic signal controller is via discrete logic (contact open/contact closed), which is limiting and needs to improve. For example, data such as bus number and passengers loading must be available for integration into control algorithms that might selectively provide priority depending on how late the bus was or how many people were on board. Similarly, much of the information provided by image-based vehicle detection equipment that can track vehicles or measure queue length is currently discarded before it reaches the traffic signal controller because the detection equipment must emulate the contact open/contact close function of a loop detector. Traffic signal systems will require that emerging sensors not only use new technology, but also convey new information to the control system.

Application of Traffic Models

Many modeling procedures and techniques have been tried over the years and have achieved varying levels of acceptance and use. These models can be classified as macroscopic or microscopic. Macroscopic models are based on average flow rates and average signal timings. They are particularly useful for signal system timing design software because they provide efficient procedures for formulating objective functions used in optimization logic. In the past decade, many of the macroscopic models have incorporated more detail to account for actuated signals and coordination between them. However, these macroscopic models only provide analytical estimates of average system performance and do not provide insight into the actual signal system operation, particularly during nonsteady-state conditions such as emergency preemption or timing plan transitions.

Microscopic models are based on car-following theory and cycle-by-cycle signal times. These models have significant potential to evaluate and visualize alternative control concepts for traffic signal systems because they consider the car-following dynamics of traffic streams and they can model many of the characteristics of advanced systems such as coordinated actuated controllers. These microscopic simulation procedures can be used to analyze and tune coordinated-actuated systems directly, because they consider a majority of the parameters used in modern, coordinated-actuated signal systems. However, microscopic models have not incorporated the wealth of new research conducted to enhance macroscopic models and highway capacity manual procedures. So, even though simulation packages provide a reasonable picture of how basic signal systems will operate, many practitioners view the simulation models skeptically because of this discrepancy. Given the potential of these tools to advance the state of the practice and evaluate alternative traffic signal systems, there is a need to reconcile macroscopic and microscopic modeling procedures.

Improved Design Procedures

Current design practice is largely based on individual preferences, so the ability to resolve the effects of alternative designs objectively is limited. Sound traffic simulation based on an accepted microscopic simulation package could lead to better practice through the ability to understand alternative design decisions and to evaluate them quantitatively. The development of an accepted reference model for evaluating a variety of alternatives, including alternative traffic signal designs and controller settings, would greatly improve the state of the practice.

Coordination of Research Efforts

The source of funds for transportation research in the United States comes primarily from two areas: government agencies—primarily the United States DOT—and retained earnings by the private sector. Because government agencies procure systems on a low-bid basis, the private sector investment largely has been in specific projects under which the government agency has defined the desired product and paid for its development.

Government-funded research has tended to be fragmented among the various states and the federal government. The Transportation Equity Act for the 21st Century has added even more emphasis on states performing their own research; this will likely fragment research even further. This fragmentation will require a new initiative for coordinating research, if complex systems such as traffic control systems are to advance.

EMERGING ISSUES AND OPPORTUNITIES

This paper has presented an overview on how traffic signal systems evolved to their present state and identified various technology and user issues that are being addressed or that need to be addressed. Market forces and technology evolution guarantee that technical issues will be addressed in the next millennium, though with varying levels of success. The resolution of institutional and user issues is much more difficult to predict, because the issues often reflect policy decisions of elected officials or changeable public attitudes. However, the profession must decide how to deal with the following issues:

- Changing or modifying the mission of traffic signal systems (and organizations that operate them) from primarily *serving the needs of automobile drivers* to *serving broader transportation needs* based on priorities of various users; and
- Raising public awareness of transportation in general and traffic signal systems in particular. The public must be educated on technological complexities, statistical uncertainties of travel demand, and benefits of long-term investments in transportation management and operations, in addition to roads and bridges.

Changing or modifying missions to serve broad transportation objectives will certainly be controversial because of jurisdictional and institutional issues. The challenges of the past have revolved primarily around resources. Resources for traffic signal systems often were limited, partly because of a limited constituency for traffic signal systems. If the customers of traffic signal systems are viewed more broadly, then the costs associated with operating and maintaining the system can be shared among more groups, lowering the cost per unit served. However, with this shared cost also comes a need to provide more services and respond to more constituencies. The array of potential services includes improved emergency vehicle operation, improved public transit service, more efficient (and perhaps safer) accommodation of pedestrians, improved response to natural hazards, improved support of national defense, and the more traditional improvements for the vehicle with a single occupant going to work. When all these users are viewed as customers with varying priority needs, the market for traffic signal systems takes on new dimensions.

The emphasis on technology in recent years has created a new, but limited, public awareness of the potential of advanced technologies to address transportation issues. This awareness has created a significant opportunity for transportation professionals to advance the operations and management of surface streets by adopting a view that these new technologies can provide services to a larger user community. To reach this new level of operation and management, a variety of educational developments must take place. Efforts must begin early to interest bright, young students in pursuing careers in transportation, as well as to develop informed future consumers of improved transportation services. Visits to the local fire or police departments should be augmented by visits to the local traffic management center. Professionals, too, must be educated in the new vision of transportation services, focusing on consumers of transportation services and their relative priorities. Transportation professionals must redouble their efforts to broaden support for their product. Finally, development of the necessary tools must continue in order to support the vision. This vision will take time to mature, but it will develop as we continue to make the best use of our extensive transportation infrastructure.

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