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DEVELOPMENTS IN TRAFFIC SIGNAL SYSTEMS

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NOTE:

This summary of papers prepared by the Committee on Traffic Signal Systems was developed by a subcommittee composed of Nathan H. Gartner, James L. Powell, Robert M. Shanteau, and Herman E. Haenel, Chairman.

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DEVELOPMENTS IN TRAFFIC SIGNAL SYSTEMS

CHAPTER ONE

INTRODUCTION

There is a growing need to reduce vehicle emissions, reduce delay, reduce traffic accidents, and reduce fuel consumption in highway transportation. One of the major methods of achieving these reductions within our urban areas is through the installation, operation, and maintenance of the traffic signal systems.

Although traffic signals have been interconnected and operated as systems since the 1920s, there is still much room for improvement in the design and operation of these systems. Many of the concepts used in modern systems were developed in the 1930s and these have merely been updated as new control equipment (hardware) has been developed.

Many of the improvements that have been made in system design have been as a result of research and many improvements can be made from similar research, in the future. Communications are needed between the traffic engineer in the field and the traffic engineer in research to develop practical systems.

The purpose of this report is to: (1) discuss the state of the art of traffic signal systems and (2) discuss areas where future research would be worthwhile. The report also discusses the use of computer models in the design analysis of systems and in the optimization of operating traffic signals individually and as part of the system.

The report summarizes 23 papers developed by the Transportation Research Board Committee on Traffic Signal Systems and as such attempts to bring traffic signal system problems and needs into focus. The report also provides many references for use by traffic engineers in traffic signal system design work. It is hoped that this report will be of benefit to traffic engineers and researchers alike in the future development of practical traffic signal systems that provide for the optimum and safe movement of people, services, and goods within metropolitan areas.

CHAPTER TWO

TRAFFIC SIGNAL SYSTEMS

Traffic engineers have placed signalized intersections into groups of related signals and operated them in an interconnected and coordinated system since the 1920s. There are basically two types of traffic signal systems, the network system and the arterial system. The network traffic signal system generally consists of 1) a central business district (CBD) together with arterial streets that could be considered as logical extensions of the CBD network, and 2) other grid systems serving heavy generators in suburban and fringe areas. The arterial traffic signal system consists of one or more signalized, arterial streets that collect traffic from local streets, carry this traffic to traffic generators such as the CBD, and distribute this traffic either at the generator or onto network system streets.

SYSTEM CONCEPT CONSIDERATIONS

Network Traffic Signal Systems

Network traffic signal systems must be capable of 1) gathering discharging traffic from the network, 2) permitting the loading and unloading of off-street parking facilities, 3) serving traffic passing through the network on one or more arterials, 4) providing for pedestrians within the area, 5) providing for traffic circulating within the area, 6) providing for high-occupancy vehicle (HOV) operations, and 7) handling trucks and other vehicles that serve businesses within the area. To carry out these functions, the overall system should be flexible and adaptable to various demands at different periods of the day and the week. Significant progress has been made in the development of sophisticated traffic signal equipment (hardware) for network control. Electromechanical pretimed intersection controllers have been replaced by solid-state microprocessor-based controllers that can provide more flexible operation. Computer system master controllers have advanced to permit more traffic control patterns and extensive data acquisition, analysis, and storage.

In terms of actual control, however, the network control concepts of the 1930s still serve as the base line of today's systems -- just implemented with new hardware. The state of the art can permit improved systems. These include: 1) extensions and improvements on the current concepts; 2) control systems concepts that dynamically reconfigure the network on a cycle-by-cycle basis; and 3) concepts that maintain CBD cordon counts of vehicle accumulation within the grid network to institute restricted entry timing plans. Extensions of current concepts could include: 1) use of data for analysis of each timing plan -- a self-evaluation of performance, 2) automatic development of new timing patterns based on data collected at specified locations, and 3) self diagnostics for maintenance purposes. Although most of these concepts are being studied and developed, considerable work will be required in the future in order to achieve dynamic systems that will provide optimum operation of network systems and coordination with adjacent arterial systems.

There is also a need to consider the requirements of the smaller cities (5,000 to 50,000 population) and to provide systems that will be easy to operate and maintain. Work in this area will require an emphasis on a more basic system that will take advantage of some of the larger network functions, such as traffic pattern implementation from a central computer master and the monitoring of intersection control equipment in order to reduce maintenance.

Arterial Traffic Signal Systems

The Institute of Transportation Engineers (ITE) informational report, entitled "System Considerations for Urban Arterial Streets," defines an arterial as a street that "has a primary function to move traffic. This type of facility connects freeways, major traffic generators, and serves major through movements. In addition, it carries the majority of the community traffic. It is the arterial that provides routes of major transit service and serves as the collector for traffic generated on local roads." By using this definition, it is possible to develop an overall objective for an arterial system as the provision of smooth traffic flow along the primary roadways. There are instances, however, where this objective can run into serious difficulties. Instances where these difficulties arise, include

- Crossing arterials that prevent the distinction between side streets and arterial facilities,
- Arterials that are adjacent to networks that generate major cross street traffic flows,
- Arterials that have large distances between intersections that limit the effectiveness of progressive timing,
- Arterials with major strip development that prevents effective implementation of a progressive signal operation, and
- Arterial traffic volumes and geometrics that, in combination, provide significantly lower critical lane volumes and lower green time requirements than those needed by the cross streets.

These are but a few of the many factors that should require a rethinking of the design and operating policy that emphasizes through arterial flow at the expense of all other movements.

Planning for the implementation of an arterial traffic control system may be the most important phase of a system implementation. Yet it is all too often ignored because of adherence to existing agency operating philosophies. Use of traffic volume and analysis data (such as turning movement counts, variability of traffic patterns, and a comparison of through traffic as compared to turning movements), permits analysis to be performed in three stages:

- Definition of objectives--Several objectives are possible, each leading to the selection of greatly different traffic control policies, for example:

  -Maximizing bandwidth is desirable under conditions of heavy through traffic and light side street or turning movement traffic,

-Minimizing overall stops and delays for both main street and side street traffic,

-Reducing the duration and extent of congestion, and

-Encouraging the use of certain arterial facilities.

These objectives may require differing control equipment and techniques, depending on the objective and the characteristics of the arterial.

• Identification of alternative strategies and types of equipment--This stage of the planning process requires a knowledge of the state of the art of available traffic control masters and intersection controllers. Typical alternatives that might be considered would be time-of-day coordination by using time base coordinators or time clocks, more sophisticated arterial masters, or a central computer.

• Evaluation of the most suitable form of control through the development of estimated costs and benefits of each alternative (which must include operation and maintenance requirements as well as initial installation costs).

These three steps are straightforward and used in developing highway improvements. In many communities, however, the traffic engineering staff uses the conventional wisdom that arterial flow must always be favored and that, as congestion increases, the investment in the signal controls system must also increase. As a result, arterials that have moderate traffic frequently are not coordinated, and those that have highly predictable heavy traffic flows use expensive traffic-responsive systems equipment. Also, arterials are often installed and operated as isolated systems without consideration to adjacent street networks and crossing arterials.

SYSTEM, DESIGN, INSTALLATION AND MANAGEMENT CONSIDERATIONS

Considerable study and analysis should be given to the design of each traffic signal system. To ensure a suitable overall system, the needs of the citywide traffic control system should be considered to determine how the needs of each subsystem that constitute the citywide system interrelate with each other. Further hardware (intersection and master control equipment) interconnection (both present and future interconnection) needs must be considered in order to ensure that the equipment installed at present will also be satisfactory in the future.

Two principal references relate to the analysis and initial design stages of network signalization. These are "The Traffic Control Systems Handbook" (1), and NCHRP 3-18(3) "An Approach to Selecting Signal Systems" (2). The handbook has substantial background data for system planning, design, and implementation and is the most complete single reference source. The NCHRP report provides a step-by-step approach for determining the areawide requirements of control and for selecting from various traffic control alternatives. Other planning and design references include the FHWA report on communications alternatives (3), and a distributed multilevel traffic control system (4). Also at the design level, FHWA prepared a comprehensive checklist (5), and documentation for the Extended Version of the Urban Traffic Control System (UTCS) software (6) that have been used in developing system specifications.

Three computer models have been developed for use in analyzing network design requirements and in providing opitmum traffic signal timing. These models are NETSIM, (7) TRANSYT-7F, and SIGOP III. These computer models made it possible to consider the many variables involved in network traffic control and provide measures of effectiveness for various operational schemes. These models can also be of assistance in evaluation of operaton and upgrading of the network traffic control system (8).

As with network systems, models are available to assist in the analysis, design, and operation of the araterial. The Arterial Analysis Package (AAP) (8) provides a series of computer models, including the SOAP, PASSER II, and TRANSYT models, which can be of considerable assistance to the engineer. Also, the NETSIM computer model can be of help in analyzing various approaches to providing improved operation within a network and along one or more arterials. The NETSIM analysis approach includes pavement widening, geometric changes, changes in the type of traffic control applied, and changes in traffic signal patterns.

The computer models such as NETSIM, TRANSYT, and AAP can be of considerable help in the initial design analysis, but they have not been used adequately and training courses are provided infrequently. Also, the cost of obtaining the necessary traffic data discourages their use.

Once the initial design phase is completed, additional considerations need to be made during the final design and implementation phases. These include the following:

• It is important to consider the installation and coordination of adjacent systems in the future. If there are adjacent systems that may need to be coordinated, hardware used in each system will need to be compatible with the adjacent system hardware. Considerations for determining if adjacent systems will need to be interconnected or otherwise coordinated are discussed in NCHRP 3-18(3), "An Approach to Selecting Signal Systems."

• It is vitally important to properly locate and install intersection and system sampling detectors. The procedure for determining the number and location of sampling detectors is still considered an art and these techniques need to be refined.

• The type of communication system to use needs to be determined. The communication system is the most expensive element to install. There remains a need to develop low-cost communication systems (e.g., radio, microwave, and power line communicators).

• Signal timing is one of the most important factors in determining overall system effectiveness. As previously stated, the collection of adequate traffic data is important. In addition to providing more training courses, lower cost data collection techniques should be developed to encourage more frequent signal retiming.

• It is vitally important during the design stage to ensure that funds and personnel will be available to operate and maintain the system. If proper operation and maintenance are not provided on a year in and year out basis, the system will not maintain its desired effect and the initial benefits will be lost along with the funds spent on the system. More study needs to be provided in determining the needs for system operation and maintenance, and more training courses need to be developed to train those persons involved in the maintenance operations activities.

There are no monumental works concerning procurement and implementation. Essentially all projects follow the procedures developed by state and city agencies for controlling and managing standard construction projects. Four approaches being used include: 1) standard turn key contractor bids; 2) two-stage approaches involving technical certification and costed (negotiated) bids; 3) systems management where a single consulting firm may be used in the roles of technical advisor, software supplier, and construction manager and 4) systems management that provides for a consulting firm to carry out the work described in both 2 and 3.

It is important to evaluate a new system and document the magnitude of actual improvements in comparison to forecasted benefits of the control system. Most operating agencies have not developed an ongoing evaluation process for use in determining benefits from existing improvements and in developing guidelines for future updates, timing changes, and general operational refinements.

Once a system is in operation, its upgrading can take two forms: upgrading to expand its area of control by adding new intersections or upgrading the hardware or software to handle new functions. There can be a problem from a cost standpoint in expanding a system by adding intersections and making computer function (hardware and software) changes. Although intersections are added to a system, very few functional upgrading projects are attempted.

ASSESSMENT OF CURRENT and FUTURE SYSTEM NEEDS

Although the "Traffic Control Systems Handbook" and the NCHRP Report 3-18(3) are excellent overall primers, they are somewhat out of date and not sufficiently detailed to be used as design guides. Revisions to the handbook are expected to be completed by 1985. It appears that the revision will provide more emphasis on design and implementation. There is still a deficiency in support documents for preparation of final design and bid packages. The UTCS checklist is not applicable because of age.

Although advances have taken place in hardware development, operational control technology has not kept pace. As previously stated, pioneer advances are needed in improving the state of the art in traffic control technology for both network and arterial systems. Likewise, there is still a need to improve traffic management capabilities involving traffic data analysis and use of computer models for analysis and signal timing optimization.

Today's computer-based systems offer a significant tool for use in maintenance management through self-reporting of hardware malfunctions. There is still a need to expand this technology to identification, logging, and diagnosis of failures in individual components and subassemblies. Such technological advancements will be of considerable benefit to the maintenance personnel.

Because of the advances in hardware technology, maintenance and traffic operations personnel who have more advanced skills are needed. Trained personnel are required to operate and maintain the high-technology systems being installed. Since governmental agencies are often not able to hire a sufficient number of skilled personnel for all their maintenance needs, some contract maintenance for central master computers and communication equipment.

Arterial roadways are among the most important facilities of the urban area street system. Yet often they are controlled by using cookbook traffic control solutions. More attention must be given to the planning and design of these systems.

Past efforts have focused on hardware development for signal control. There is a need, however, to continue developing means for capitalizing on the hardware development and on design analysis techniques. There is also a need to improve on system management. Inadequate attention has been given to the requirements for managing (operating, evaluating and maintaining) the system. This is the area where pioneer efforts are now and will be needed in the future.

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CHAPTER THREE

SYSTEM HARDWARE/ARCHITECTURE

This chapter discusses existing and emerging technologies in the design of traffic signal control systems and their possible impacts relative to systems architecture, systems procurement, and research activities.

LARGER CITY NETWORK SYSTEM DEVELOPMENTS

There is a need in many larger cities to obtain the optimum operation from their traffic signal systems in order to improve the level-of-service operations, decrease vehicle emissions, decrease fuel consumption, and reduce accidents. This can be achieved through improved design of traffic signal systems. The amount of improvement is limited in many instances to the capabilities of trained maintenance and traffic operations personnel. Varying degrees of sophistication and resulting improvements can be obtained depending on the city's financial, operational, and maintenance capabilities.

Present Architecture

Most of the systems that have been installed in the United States, over the last several years, have a similar architecture: a smart central computer and a dumb pretimed or actuated intersection controller. Although new actuated controllers installed as part of such systems usually use the new generation of microprocessors, the controller is still only used as a dumb controller, even though it has considerable potential for much more sophisticated applications. Communication is via owned or leased dedicated conductors, typically telephone-type cable. Time division or frequency division multiplexing techniques provide the needed communications capacity at minimum cost. Only few variations from this typical architecture have been used.

New Technologies

Rapid advances in microprocessor technologies have generated a number of preliminary concepts that could provide comparable system performance at reduced cost or improved performance at the same cost. However, due to the substantial efforts involved in the development and implementation of radical system designs, the use of these concepts in new systems has been evolutionary rather than revolutionary.

There is also an apparent trend toward new communications media. New, low- capacity, low-speed media include air path optical communications (laser beams), radio communications, and power line communications techniques. High-speed, high-capacity media include coaxial cable fiber optics and microwave radio. A 1978 FHWA report entitled "A Communications Trade-Off Study for Computerized Traffic Control," discusses existing and emerging communications technologies and addresses, to a limited degree, communications trade-offs applicable to various types of systems architecture (1).

Possible Architectures

Considering the present and emerging technologies in processors, communications, and system functions, a large variety of system configurations is possible. However, to facilitate a meaningful discussion, a limited set of architectures is considered in Table 1. It is assumed that in each case the system is modular; for instance, there could be different timing plan modules; time-of-day, traffic-responsive, etc. Other modules could be developed for a wall map, television (TV) or cathode ray tube (CRT) display, critical intersection control (CIC), and measures of effectiveness (MOE) printouts. The modules can be constructed in hardware and software, or in software only.

Following is a brief description of the various types of architecture listed in Table 1.

Type 1 - Typical present system, centralized processor, dumb local, dedicated, high-capacity communications.

Type 2 - Three-level system, bulk of processing done by intermediate controllers. Several variations of these have been constructed or planned -- however, two-level systems may become the most logical alternative as more powerful microprocessors become commonplace.

Type 3 - Two-level system, dedicated high-capacity communications, bulk of processing done at central, some detector processing and data compression at local. Essentially a Type 1 system with simple modifications to take advantage of increased power of microprocessor-based local.

Type 4 - Two-level system with bulk of processing accomplished at local. Timing plans stored at locals. Central communicates with local via low capacity, dedicated communications once every (say) 5 minutes. Locals transmit fully processed detector based data and intersection subsystem status. Master provides timing plan instructions for next 5 minutes. Timing plans in table are downloaded by central and called up by local on a time-of-day basis.

A Basic System

A further possible trend is towards scaled-down systems. It has been noted that many agencies that have purchased full-scale systems find that they do not need or use all of the features of these systems. There has emerged the idea of a Basic System, as conceived by the TRB's Traffic Control Devices Committee (2). This system would not provide a traffic-responsive control as a basic design feature, thus avoiding the need for detectors and the extensive processing devoted to detector data; nor would it include a map display, critical intersection control, and MOE printouts. It would, however, provide implementation of timing plans on a time-of-day or manual basis from a central location, limited malfunction detection, and stand alone operation. It would still have the option for traffic-responsive control should such control be required within a portion or all of the system. Overall, it would constitute a traffic management tool that is easy to use and designed to put timing plans on the street with a minimum of effort and cost. It is believed that such a scaled-down system could be accommodated on a central microprocessor rather than the minicomputer used in most network systems. Such a system would particularly be suitable for smaller communities or in some sections of larger communities.

TABLE 1
TYPICAL TYPES OF ARCHITECTURE

Item	Type 1 Present	Type 2 Some Current Use	Type 3 Future	Type 4 Future
Processor Configuration	Smart Central (mini) pretimed and/or actuated locals	Micro- or mini-central, & intermediate processors; pretimed and/or actuated micro-based local	Micro- or mini-central; micro-based local with Time Base Coordination	Micro- or mini-central; micro-based local with Time Base Coordination
Timing Plans Stored at	Central	Intermediate, down loaded from central	Central	Local
Standby Operation	Semisynchronized pretimed control or isolated actuated	Semisynchronized pretimed control or isolated actuated	Time Base Coordinated single timing plan or actuated	Full complement of Time Base coordinated time of day (TOD) plans
Detector Processing	At Central	At intermediate, tabular data transmitted to central	Some processing at local, rest at central	At local, tabular data transmitted to central
Nature of Communications	32 times/sec.; short messages	Once/sec. inter. message	Once/min. inter. message	Once/ 5 min. longer mess. & once/sec. supplementary
Communications Medium	Dedicated cables or channels multiplexed, owned, or leased	Dedicated cables or channels multiplexed, owned, or leased	Dedicated cables or channels multiplexed, owned, or leased	Dedicated cables and tel. drops; air paths

Problems in Systems Procurement

As the new technology emerges, a large variety of system configurations can be conceived that would be practical from a cost and effectiveness basis. This variety could result in a serious problem relative to the procurement of systems. Users, or their consultants, would each study the needs of the respective communities and the contractors would then tailor-make each system. There are many disadvantages to this approach: The design process would be involved and expensive and the decision-making process would be difficult for the user because many of the trade-offs would, by necessity, be poorly defined or be based on assumptions concerning the availability of new components or new technology. Furthermore, such a tailor-made system would be costly to construct and would be likely to suffer numerous start-up problems.

Is systems standardization a solution? The users and the signal industry were faced with a comparable problem concerning actuated intersection controllers at the time solid-state and microprocessor-based technologies were first introduced. This was solved very effectively by development of the National Electrical Manufacturers Association (NEMA) standards. A similar NEMA approach may be applicable to signal systems and indeed, was recommended by the Workshop on Control Systems for Smaller Communities at the Henniker Conference (3) during 1981.

Research and Development Activities

The FHWA is contemplating two research studies that address the matters described herein. One would be on the interchangeability of traffic signal system communication hardware. It would analyze data communications equipment used in current traffic systems and consider the feasibility of developing a limited number of functional specifications for interfacing the equipment with traffic systems hardware and, if feasible, develop appropriate functional specifications. A second study would be on functional specifications for microcomputer-based traffic signal control systems to serve as an alternative design to the present UTCS system. It will explore various systems configurations and provide a set of functional specifications. This study will also provide a catalog of systems and optional features that will enable the users to construct a set of specifications that will reflect their particular needs. It is hoped that this exploration of the various architectual concepts would be useful to users, engineers, and the signal systems industry.

SMALLER CITY NETWORK SYSTEM DEVELOPMENTS

The small urban areas referred to are those that have populations between 5,000 and 50,000. In the United States, there are approximately 4,500 such areas with a combined population of 65 million; i.e., a significant proportion of the entire population. Problems of traffic congestion in small urban areas are not as serious as those in large urban areas. But they can be bad enough to prompt a demand for new highway facilities. Poor signal control of intersections is often a primary cause of the congestion. The signal control encompasses a number of activities relating to the choice of hardware and software technologies, contract management, design and installation of control systems, timing of signals, operation and maintenance of facilities, etc. This section discusses the development of signal control technologies for small urban areas.

State of the Art

The advancement in signal control hardware technologies is far ahead of the development of software support needed for their efficient use. At the present time, the most advanced form of signal control is areawide control by using centralized computers. This form of control is not new and is no longer limited to very large cities. The control may be based on timing patterns generated off-line or rely on on-line optimization of signal timing (4-7). Time- of-day pattern selection by using pretimed signals is currently the standard of areawide control in the United Kingdom (U.K.) (8). Real-time control has been demonstrated capable of providing a better control efficiency than off-line control (9).

In recent years, traffic-actuated controllers have replaced pretimed controllers as the backbone of signal control in many areas. Guidelines for the design and operation of these controllers and detectors are currently available (10-14). Our understanding of the performance characteristics of traffic-actuated control systems, however, is still limited. It appears that many practicing engineers do not have a capability to evaluate alternative timing plans of such control systems. Inefficient use of the control hardware is common. A convenient evaluation tool to aid in the timing design is still needed.

It is doubtful to what extent the advancement in signal control technologies has benefited or can improve signal control practice in small urban areas. It appears that small urban areas can use the advanced control hardware adequately but are very weak in their capabilities to provide software support. In some states, traffic-actuated controllers are being used at many of the signalized intersections of small urban areas.

Microprocessor-based controllers (15), are being used for virtually all new installations and are expected to play an increasingly significant role. Despite the ability to adopt new hardware technologies, little progress has been made in signal timing practice. Computer-aided signal timing tools developed in recent years are not being used extensively. In fact, the use of computers is primarily for data processing, highway capacity analysis, and highway geometric design. Signal timing based on trial-and-error in conjunction with a short-term field observation of the signal operation is not rare. There seems to exist a wide gap between the development of software technologies and the implementation of such technologies for signal control in small urban areas. This gap is unlikely to narrow unless future development of signal control technologies takes into account the constraints imposed on signal control practice in small urban areas. Recent efforts in developing signal control software tend to emphasize sophisticated computer-based timing algorithms. The manpower, training, and computer facility requirements for implementing such algorithms often exceed the in-house capability of an agency responsible for the signal control in small urban areas.

Under these circumstances, areawide control using mainframe computers is not presently practical for small urban areas. Signal control software packages that require substantial personnel training and computer facilities will only have limited applications in these areas. Microprocessor-based controllers are likely to become the mainstay of signal control because of their flexibility and relative ease of maintenance.

Microprocessor applications (16) for signal control systems management also have a great potential in small urban areas. However, if the past trend in software development continues, a significant improvement in signal control in small urban areas is not likely to materialize in the near future. How to enhance the compatibility between the signal control technologies and the capabilities of the traffic engineering agencies in small urban areas is the challenge of today and of the future. The Basic System described previously may be a step in this direction for small urban areas.

ARTERIAL SYSTEM DEVELOPMENTS

Cities large and small, as well as suburban areas, have arterial streets that move traffic to and from the CBD and other major generators (i.e., office complexes, industrial areas, college, and recreational areas). It is important to provide traffic operations along these arterials that are adequate for the current and future needs of traffic. This section discusses technologies for arterials.

Where traffic volumes are predictable and where capacity constraints are not excessive, fixed-time systems coordinated either through time base coordinators or interconnect cable provide satisfactory operation. Fixed-time signals can also provide actuated phases that deduct time from a specified phase on vehicle demand. Where one or more intersections requires multiphase operation, full-actuated controllers can be incorporated into the coordinated system. Since traffic patterns are predictable, time-of-day operation with or without a master controller provides a practical operation. These systems are available at present from traffic signal manufacturers through use of state-of-the-art equipment. The systems can provide up to four cycle lengths, three splits per cycle length, and three offsets per cycle length. Development work is underway whereby traffic pattern changes can be made by downloading (placing) new paterns from a central controller into a microprocessor-based intersection controller through use of the interconnect cable or leased telephone lines.

Where traffic patterns are not predictable during the day or during the week, traffic-responsive systems will provide improved traffic operations. Traffic-responsive systems, which use microprocessor-based master controllers, are available from traffic signal manufacturers. These master controllers generally provide four traffic patterns and three offsets per cycle length. In some instances sampling detectors are placed on the cross-streets so as to provide up to three splits per cycle length.

Another system supplied by a manufacturer has provided excellent operation where heavy traffic movements are predominantly in one direction during the peak periods. The master controller determines the desired cycle length for each cycle and transmits this cycle downstream to succeeding intersections. The platoon moves with the cycle length. While the system is operating in preferential flow mode each cycle length can be different from that for the previous cycle. When the traffic flow along the arterial street reaches a balanced two-way flow, a designated cycle length with two-way progression is provided for a designated preset period of time. The flexibility of operation provided during the predominate inbound and outbound flow is an example of new concepts that can be made available through use of the microprocessor state-of-the-art equipment.

Traffic-responsive operation can also be obtained along an arterial street through mutual coordination. The DARTS system, which stands for Dynamic Artery Responsive Traffic Signal system, consists of a series of NEMA full-actuated traffic signal controllers, each with an external logic modular Dynamic Coordination Unit, (17). The system permits each intersection to function in its normal isolated full-actuated mode until a platoon (Queue) is detected along the arterial at an intersection. Once a platoon is detected, the upstream intersection controller advises the adjacent downstream intersection controller that a platoon is on the way. Through the use of three timers, the adjacent downstream intersection controller coordination unit permits the cross street and opposing left-turn phases to occur (if there is a demand) and then forces off these phases in time for the main street platoon to pass through the intersection. Should the cross street or left-turn demand be unfilled for a period of time at an intersection, however, the intersection is dropped from the system for one cycle to permit clearance of traffic on all phases.

The system uses two Dynamic Coordination Units between each intersection, one pair for each direction of travel. The DARTS system was developed by the Texas State Department of Highways and Public Transportation (TSDHPT) and has been successfully implemented.

The TSDHPT has also developed the FACTS system which stands for Flexible Advanced Computer Traffic Signal System (17). The FACTS system was developed for use along arterial highways, freeway frontage roads, complex freeway interchanges involving traffic signals, and small grid networks. The FACTS system is being installed where there are numerous unpredictable patterns, arterial capacity restraints require improved use of the cycle time, and the arterial or system serves many functions during the week (i.e., commuter, business, school, recreational). The system uses a 64K computer that can permit individual phase (movement) control of 20 to 24 intersection controllers. Additional intersections can be controlled on an individual basis provided a fixed head disk is used. The computer uses the hold, skip, and force off inputs for each phase of the NEMA full-actuated controller to provide any desired left-turn sequence of operation. The use of these command functions also permits unused time from the actuated cross street and left-turn phases to be allocated to the main street phases so as to improve the overall intersection operation and/or main street progression. The computer also controls the phase operation and left-turn sequence (dual left lead, lead-lag, and dual left lag) for each fixed-time controller.

Communication is provided by two pairs of wires from the computer to each intersection controller and a microprocessor-based interface unit at each intersection. In addition to data acquisition and traffic control transmission, the interface unit is capable of monitoring and reporting intersection control and detector malfunctions.

Features of the System

• Any combination of left-turn sequence (i.e., dual left lead, dual left lag, lead-lag) can be assigned at each intersection of each pattern. This permits improved progression along the arterial.

• Each intersection can provide up to six designated splits per cycle length-offset pattern. Each split pattern is chosen from system detectors.

• A total of 188 cycle-offset-split pattern combinations are available for each of six subsystems, which permits use of multiple patterns during peak periods and special traffic conditions.

• Ability to choose the number of transition periods (one to three cycle lengths) when changing offset from each pattern to another (e.g., the transition can be made during one cycle when changing from Pattern 1 to Pattern 2 and three cycles are required when changing from Pattern 2 to Pattern 188).

• The percentage split for the shortest route transition is adjustable. Currently a 70/30 split is used; longer cycle lengths are used at an intersection to achieve a 0% to 70% change and a shorter cycle length is used to achieve a 70% to 99% change.

• The base offset point used in a transition floats." When a pattern change occurs, the first intersection offset point reached is used as the new system base offset point for the new pattern.

• The use of six subsystems permits critical intersection or critical segment operations. This is especially helpful when shift times and office times (or flex-time) traffic generation, which occurs at different times, affects different subsystems and when accidents occur along the facility.

• System traffic patterns and equipment monitoring can be achieved from a central location as can the downloading of new traffic patterns.

Although the FACTS system is small in size and of the special function type, larger systems could benefit from some or all of the functions implemented in the FACTS system.

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CHAPTER FOUR

STRATEGY DEVELOPMENT

State-of-the-art traffic control strategies in urban: networks are calculated off-line, stored in a computer's memory, and selected for implementation by various real-time criteria such as time-of-day, level of congestion, or special events. There exists also logic for critical intersection control and various traffic-actuated schemes at individual intersections. Many research efforts have been directed toward the development of new strategies that would relieve the traffic engineer from the constant burden of rata collection and strategy revision, and, at the same time, provide an improved level of traffic performance. Experiments have been conducted with various on-line signal control plan optimization techniques, (Second and Third Generation) as opposed to the existing off-line techniques (First Generation). Results have been mixed. The emergence of microprocessor-based controllers provides new opportunities for the development of responsive traffic control strategies.

This chapter reviews results from past studies conducted in the United States, Canada, and the United Kingdom and analyzes their implications with respect to the development of improved generations of urban traffic control strategies (1-3).

STRATEGY DEVELOPMENT AND TESTING

This section reviews some of the major experiments with computer-controlled strategies that were conducted during the past 15 years in Great Britain, Canada, and the United States. The nomenclature developed in the UTCS project (described below) is used to label the different types of strategies:

- First Generation Control -- 1-GC (off-line optimization, on-line implementation)
- Second Generation Control -- 2-GC (on-line optimization, stepwise steady-state flow conditions)
- Third Generation Control -- 3-GC (on-line optimization, responsive control)
- Critical Intersection Control -- CIC

The British Experiments

A number of different strategies for controlling traffic signals in a network have been subjected to full-scale tests by the Transport and Road Research Laboratory (TRRL) in Great Britain (4). Most of the testing was carried out in Glasgow, where a computerized system of 80 traffic signals covering an area of about 3 sq. km. has been instrumented since 1967. The strategies that were tested fall broadly into three categories:

1. Fixed-time plans based on historical data and calculated off-line by a computerized optimization technique. The three techniques tested in this category were COMBINATION METHOD, TRANSYT, and SIGOP (1-GC strategies).
2. Strategies in which each signal can respond individually to traffic detected on the approaches, subject to some basic coordination scheme similar to Gartner (1). Two strategies were tested in this category: FLEXIPROG (a vehicle-actuated flexible progressive system), and EQUISAT (equal degree of saturation) (1-GC with CIC).
3. Responsive strategies in which all the signal settings are calculated on-line by using a real-time algorithm and information from detectors, including DYNAMIC PLAN generation (2-GC strategy) and PLIDENT (platoon identification) (3-GC strategy).

The results of the tests are summarized in Table 2.

As a result of this series of experiments, TRRL concluded that the most effective strategy is to operate the traffic control system on a fixed-time basis by using a library of signal timing by plans that were prepared off-line based on historical data.

TABLE 2
SUMMARY OF BRITISH EXPERIMENTS

Control Strategy	Results of Tests
COMBINATION METHOD	12% improvement in travel time over existing Glasgow system which was only partly interconnected
TRANSYT	4% improvement over COMBINATION METHOD
SIGOP	Same level of effectiveness as TRANSYT
FLEXIPROG	Equal to COMBINATION METHOD (Glasgow) 2% better than CM (West London)
EQUISAT	Same travel times as COMBINATION METHOD
DYNAMIC PLAN	9% inferior to TRANSYT (Madrid)
PLIDENT	Average of 29% longer travel times than COMBINATION METHOD

Development work is continuing in on-line development and implementation of real-time system traffic control by TRRL with the SCOOT System, which is commercially available. The SCOOT System automatically develops and implements new traffic control patterns each 2-1/2 to 5 minutes and changes intersection splits each cycle length when traffic patterns change within the system.

The Toronto Experiments

An extensive study of the effectiveness of various control strategies was conducted in metropolitan Toronto (5). In total, four different strategies were evaluated with respect to an existing strategy based on an arterial preference method named SIGRID. The first three strategies were of the 1-GC type, while the fourth was a 2-GC strategy named RTOP (Real-time Optimization Program). Field evaluations were conducted in two different locations: a CBD arterial-based subnetwork and a suburban subnetwork. Results are summarized in Table 3 which indicates that among the 1-GC strategies the COMBINATION METHOD was slightly superior, and the Real-time Optimization Program gave mixed results.

TABLE 3
SUMMARY OF TORONTO EXPERIMENTS

Strategy	CBD	Suburb
SIGOP	Equivalent to Existing	Existing better by 3.2%
TRANST	Equivalent to Existing	Existing better by 2.5%
COMBINATION	4.5% better than Existing	2.8% better than Existing
RTOP	4.8% better than Existing	Existing better by 6.3%

The Urban Traffic Control System

The Urban Traffic Control System (UTCS) (6) research project was initiated by the U.S. Department of Transportation (DOT) in 1967 to explore the potential advances in both software and hardware offered by computer control systems at that time. It consisted of a 200-intersection computerized test system in Washington, D.C., comprising arterials and a grid network with 512 vehicle detectors and extensive data processing, communications, and display equipment. The project was directed toward the development and testing of a variety of network control concepts and strategies, divided into three generations of control, as given in Table 4. The different generations can briefly be characterized as follows:

- First-Generation Control (1-GC) -- This mode of control uses prestored signal timing plans that are calculated off-line based on historical traffic data. The plan controlling the traffic system can be selected on the basis of time-of-day (TOD), by direct operator selection, or by matching from the existing library a plan best suited to recently measured traffic conditions (TRSP). The matching criterion is based on a network threshold value composed of volumes and occupancies. Frequency of update is 15 minutes. Software for 1-GC also includes logic to enable a smooth transition between different signal timing plans, a critical intersection control (CIC) feature that enables vehicle-actuated adjustment of green splits at selected signals, and a bus priority system (BPS) at specailly instrumented intersections. Plans can be calculated by any off-line signal optimization method; TRANSYT-generated plans were selected fof testing in UTCS.
- Second-Generation Control (2-GC) -- This is an on-line strategy that computes and implements in real-time signal timing plans based on surveillance data and predicted volumes. The optimization process (an on-line version of SIGOP) is repeated at 5-minute intervals; however, to avoid transition disturbances, new timing plans cannot be implemented more often than every 10 minutes.
- Third-Generation Control (3-GC) -- This strategy was conceived to imple- ment and evaluate a fully responsive, on-line traffic control system. Similar to 2-GC, it computes control plans to minimize a networkwide objective by using for input predicted traffic conditions. The differences compared with 2-GC are (a) the period after which timing plans are revised is shorter (3-5 minutes), and (b) cycle length is required (priori) to vary among the signals as well as the same signal during the control period (CP).

The different UTCS control strategies were designed to provide an increasing degree of traffic responsiveness through a reduction of the update interval, with a view to improving urban street network performance. However, results of extensive field testing showed that the expectations were not entirely fulfilled (6, 7).

In its various modes of operation, 1-GC performed best overall and demonstrated that it can provide some measurable reductions in total travel time over that attainable with a well-timed three-dial system. The traffic-responsive mode of 1-GC plan selection is generally more effective than the time-of-day mode. Overall 2-GC had a mixed bag, but was inferior compared with 1-GC; it demonstrated some small improvements of the arterial, but degraded traffic flow in the network. These results are generally consistent with those experienced in Toronto. In the form tested in the UTCS system, 3-GC, seriously degraded traffic flow under almost all the conditions for which it was evaluated. A summary of the results is given in Table 5 (7).

TABLE 4
CHARACTERISTICS OF UTCS CONTROL STRATEGIES

Feature	First Generation	Second Generation	Third Generation
Update Interval (Control Period)	15 minutes	5-10 minutes	3-5 minutes (variable)
Control Plan Generation	Off-line optimization selection from library by time-of-day, traffic responsive, or manual mode	On-line optimization	On-line optimization
Traffic Prediction	None	Histortically based	Smoothed values
Critical Intersection Control (CIC)	Fine tuning (splits)	Fine tuning (splits and offsets)	Not applicable
Cycle Length	Fixed within each section	Fixed within groups of intersections	Variable in time and space, predetermined for control period

TABLE 5
COMPARISON OF RESULTS OF UTCS CONTROL STRATEGIES

Traffic Responsive Strategy	Percentage change in aggregate vehicle-minutes of travel with respect to base			
	A.M. Peak	Off Peak	P.M. Peak	All Day Average
First Generation (TRSP)				
Arterial	- 2.6	- 4.0	-12.2	Not available
Network	- 3.2	- 1.9	- 1.6	
Second Generation				
Arterial	- 1.3	- 3.8	+ 0.5	- 2.1
Network	+ 4.4	- 1.9	+10.7	+ 5.2
Third Generation				
Arterial	+ 9.2	+24.0	+21.2	+16.9
Network	+14.1	0.5	+ 7.0	+ 8.2

ANALYSIS AND DISCUSSION

From the studies cited above, one may erroneously conclude that a library of timing plans generated off-line, based on historical data (from another month, perhaps another year; but, for the same time period of the day), is more effective than timing plans generated on-line, based on very recent data (past 15 minutes, or 5 minutes, or 3 minutes). (This assessment is based solely on traffic performance. It does not consider other factors, such as on-line/off-line trade-offs; 2-GC type strategies may be less data and manpower intensive than 1-GC in the long-run, but require more surveillance equipment, etc.) However, a closer examination of those studies indicates that the expectations of the researchers were unfulfilled not because their rationale was wrong (that traffic-responsive control should provide benefits over fixed-time control) but because of a failure of the models and procedures that they implemented to deliver the desired results. A major cause for this failure appears to be lying in the measurement-prediction cycle used by the procedures.

Most available traffic control methods claim to be traffic responsive in some sense. Even 1-GC strategies are traffic-responsive to a certain extent: Plans may be replaced at 15-minute intervals in response to predicted traffic volume changes. But, these methods are not truly responsive: they do not respond to actual traffic conditions but to hypothetical conditions -- the hypothesis being only as good as the model and the predictions used in the optimization. This is the most critical aspect in all the responsive strategies listed above.

Clearly, an effective demand-responsive traffic control system requires the development of new concepts and not merely the extension of existing concepts toward shorter time frames (i.e., going down from hourly intervals to 15-minutes, 5-minutes, 3-minute intervals, or a cycle time), and using predicted values that are less and less reliable. Data from detectors provide information about past traffic behavior from which a traffic-responsive system makes decisions which result in good control in the future. Ways must be devised to predict future traffic behavior from past detector measurements.

The basic premise has always been that on-line traffic control strategies should be capable of providing results that are better than those produced by the off-line methods. Analytical studies have indicated that if, under ideal conditions, complete information on vehicle arrivals was available, responsive control strategies could significantly reduce the delay incurred by using existing non-responsive strategies (8). To achieve this goal, the development of an effective demand-responsive traffic control system must follow some basic requirements:

- The system must be designed to provide better performance than off-line methods. Although this may seem self-evident, it was not always explicitly recognized in the development of responsive strategies in the past. In some cases it was superseded by less relevent criteria such as main street platoon progression or variable cycle time.
- Development of new concepts is needed and not merely the extension of existing concepts. As demonstrated by the experiments reviewed above, effective responsiveness is not achieved by implementing off-line methods at an increased frequency. New methods that are better suited to the variability in traffic must be developed.
- The system must be truly demand-responsive, i.e., adapt to actual traffic conditions and not to historical or predicted values that may be far off from the actual.
- It should not be arbitrarily restricted to control periods of a specified length but should be capable of frequent updating of plans as necessary.

Is such a system practical? The likelihood of its development is indicated by the continuous improvements in microprocessor technologies. By combining the potential capability of the microprocessor with demand-responsive strategies such as those proposed by Miller (9), or those used in Splits, Cycle, Offset Optimization Technique (SCOOT) (10), Sydney Coordinated Adaptive Traffic System (SCAT) (11), or Optimization of Policies for Adaptive Control (OPAC) (12), it is to be expected that very substantial advances in the state of the art can be achieved. An example of the potential benefits that can be expected from truly demand-responsive strategies is shown in Figure 1 (12). It compares the average delay at a two-phase signal-controlled intersection when timings are determined by Webster's method and by OPAC.

It is seen that this strategy can provide, under ideal conditions, up to 60% reduction in delay with respect to a fixed-time strategy. Although it is hard to expect such performance in real life, this result, nevertheless, is an indication of the tremendous opportunities that microprocessor-based demand-responsive strategies can offer. Undoubtedly, much more research and experimentation are needed to take advantage of these opportunities.

SPEED CONTROL IN TRAFFIC SIGNAL SYSTEMS

This section reviews the published literature with respect to speed control and traffic signal systems. Speed control is defined as any attempt to influence the speed of traffic -- such as keeping it below or above a specified value (generally both simultaneously). Traffic signal systems will mean any device or combination of devices that changes the message it displays to traffic on the order of every few seconds. Changeable message signs, as usually employed, are excluded because their typical display duration of many minutes removes them from the usual definition of signal.

The first attempts to influence speed with traffic signals seem to have occurred in Middletown and Bridgeville, Delaware in 1940 (1). What would now be called an actuated signal was set to give green to a vehicle as it arrived at the stop line assuming that it traveled at the speed limit from the detector. Faster vehicles were forced to stop.

The most interesting of the speed control systems is the speed signal funnel (14-19). This system, invented by Wolfgang Von Stein, was first installed in Dusseldorf, Germany in 1954. There are now several hundred speed funnels in operation in Germany.

An integral element of the speed funnel is the presignal. The presignal is a standard signal placed a few hundred feet upstream of the intersection. The presignal turns green a few seconds in advance of the intersection green and, if everything works properly, the vehicle platoon arrives at the intersection at full speed in coincidence with the beginning of green. In theory there can be a capacity increase of two vehicles/lane per cycle by eliminating lost time at the intersection (i.e., about 25-30 percent if the green is very short.) The operation of the presignal is illustrated in Figure 2 (12).

A speed funnel is a combination of presignals and speed advisory signals. If, for example, the minimum and maximum acceptable speeds are 20 and 30 mph, respectively, one can find a position and time from which proceeding at 30 mph will get one to the signal just before the current green ends whereas proceeding at 20 mph will cause one to arrive at the signal just after the next green has started. At this location one puts a changeable speed advisory sign to let the drivers know that if they proceed at 20 or 30 mph (whichever is appropriate) they will arrive during green at the signal. Note that the advisory speed sign cannot be placed closer to the signal because there it would be too late for some vehicles to either accelerate or decelerate acceptably to arrive on green. It can not be placed further upstream because there it is possible to arrive on green with any of several speeds. This speed advisory signal can use standard signal controller hardware because it only has to cycle through displays in synchronization with the downstream signal.

Figure 1. Comparison of average delay per vehicle (12).

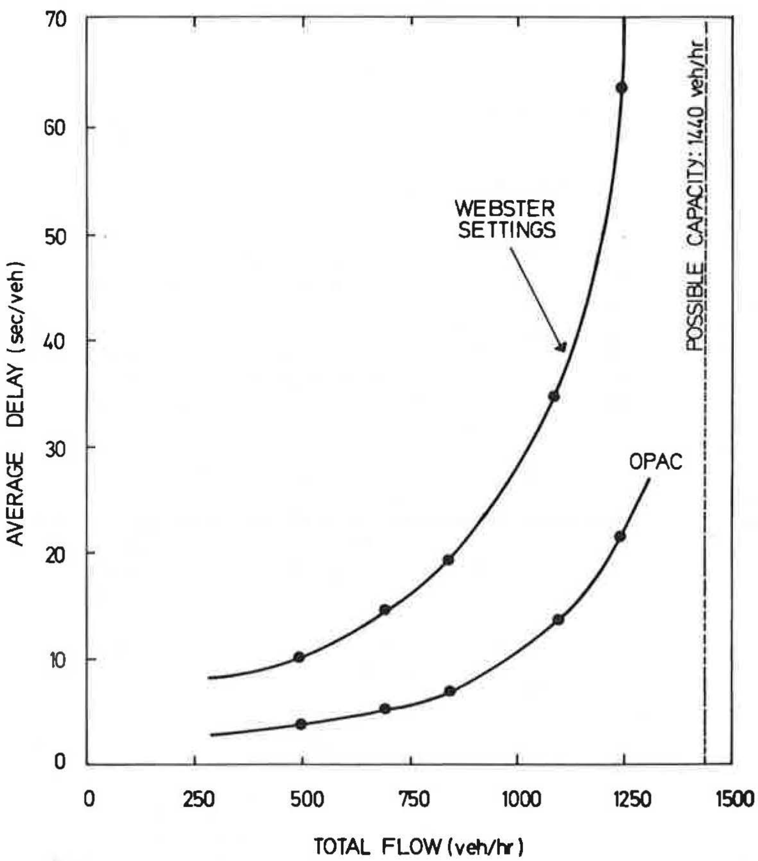
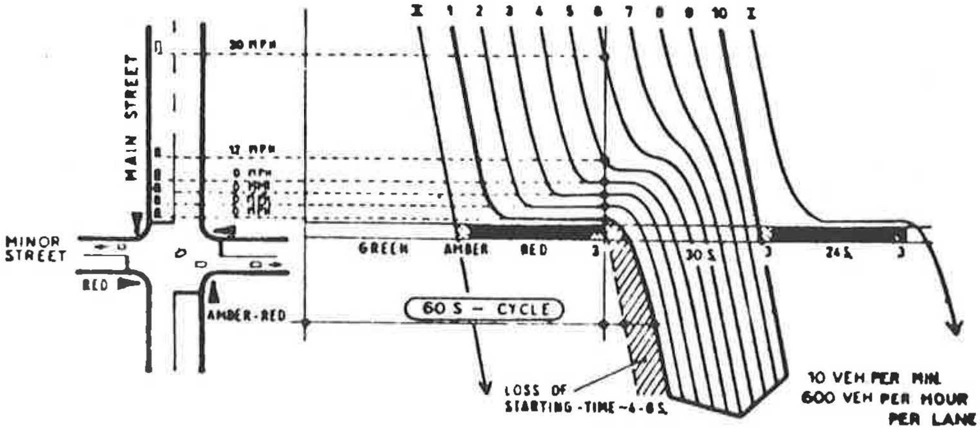
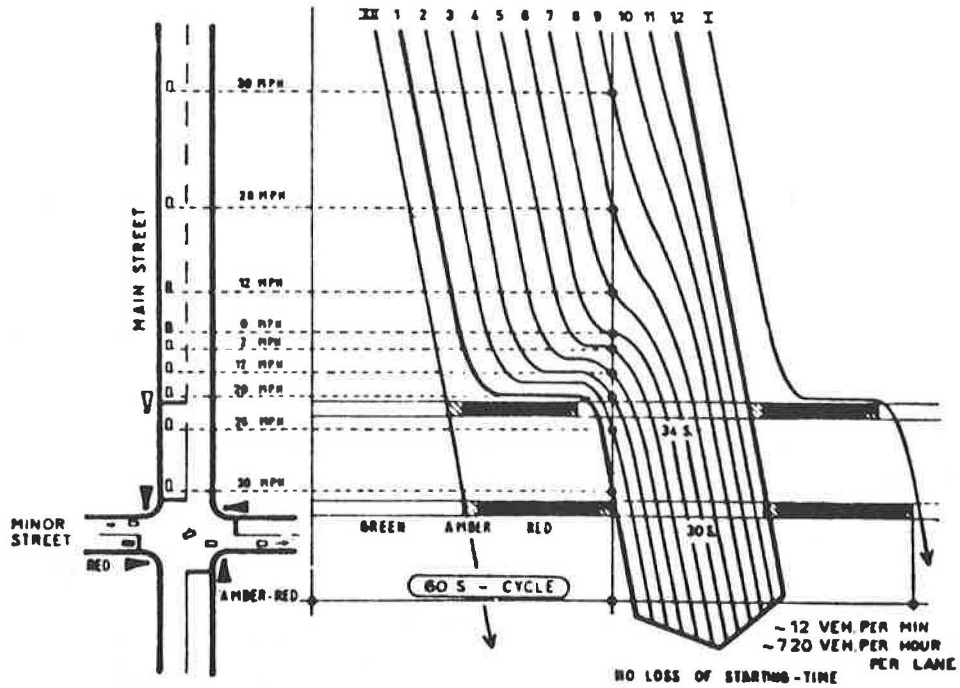


Figure 2. Time-space diagram of a crossing with pre-signal and flying start.



Time-space diagram of a normal crossing with start on the stop-line.



Presignals are inserted between the speed advisory signal and the controlling intersection signal because the lead cars (traveling slowly at 20 mph) tend to speed up and the trailing cars (traveling rapidly at 30 mph) tend to lag. Two or three presignals placed between the speed advisory signal and the intersection signal itself will catch the early speeders and stop them rather than allow them to arrive at the intersection signal early. Similarly, the end of green at the presignals will accelerate the laggards to a pace at which they can clear the intersection before the green ends there.

Speed funnels as described above are commonly used in Germany to introduce traffic into coordinated signal systems.

A very elaborate speed funnel system was built in Warren, Michigan by General Motors Research Laboratories (20-23). Reports summarizing 12 weeks (20) and 15 months (21) of experience with the system have been published. This experience seems to confirm that safety is improved and stops substantially decreased with the system. The theoretical increase in capacity was not observed. It appears that the elaborate hardware installed by General Motors is not necessary. Theoretical extensions of the traffic funnel have been published by Dare (24-26).

Recent work in the United States returns to the old principle of penalizing the speeders at a single signal. Reports (27-29) describe single signals with far upstream speed detectors. The signals rest in red but if the speed detector detects a legal speed vehicle, green is given immediately. If the speed is excessive, no actuation is made except by a detector at the stop line (presumably after a frustrating delay). The published reports are favorable [Cumming and Croft (see also 30)].

Single signals cannot do much more than penalize vehicles that are outside the desired range of speeds. The principles are well known; a survey of effectiveness is needed and, possibly, the drawing up of warrants. However, there is a strong feeling among traffic professionals that traffic control devices such as stop signs and signals are not a proper form of speed control.

The speed funnel system is well established in Germany. Its objectives are smoother flow and increased capacity but it can equally well be regarded as a speed control system. Experience is needed with such systems in the United States. Some of the General Motors research (23) on the speed funnel indicates that drivers will not pay much attention to advisory speed information no matter how beneficial it is to them. This research showed that drivers ignored beneficial speed advice unless the advisory speed coincided with the speed limit. It is not unreasonable to conclude that advisory information will be ignored until communication techniques are improved.

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CHAPTER FIVE

AUXILIARY HARDWARE AND SOFTWARE ASPECTS

This chapter discusses six auxiliary aspects, of both a hardware nature and a software nature, pertinent to traffic signal systems. These involve route diversion, changeable message displays, railroad coordination, special vehicle treatment, diamond interchange control, and pedestrian considerations. Some of the features discussed are of special interest only; whereas others should be viewed as constraints on system operation and must be carefully treated in the development of traffic signal systems.

ROUTE DIVERSION AND CHANGEABLE MESSAGE DISPLAYS

Route Diversion

Route diversion discussed here is within the context of signalized street networks and is exclusive of freeway route diversion. Thus, the scope is the diversion of traffic from one signalized arterial route to another signalized arterial route for reasons of improved operating efficiency, incident occurrence, or policy considerations (e.g., neighborhood traffic management). The tools to achieve arterial route diversion include informational and regulatory signing and control (directed diversion) and traffic signal control favoring certain routes over other routes (attractive diversion). In the latter case signal timings on preferred routes provide faster travel times than on the nonpreferred routes. The focus of this summary is almost entirely attractive diversion.

One of the obvious applications of attractive diversion is a one-way street with progressive signal timings. This strategy works well when clearly defined preferred routes are in evidence. Generally, however, signal networks are made up of many conflicting arterials, both one-way and two-way; often it is not readily apparent which should be preferred routes.

Approaches to the problem of network traffic control generally have focused on concepts of network optimization and network closure requirements. Very little work has been devoted to priority routing in developing signal plans. Experimental assessment of benefits due to such activities is practically nonexistent.

Development of signal plans to favor certain routes can be achieved in different ways. By using a network optimization tool such as TRANSYT, appropriate delay and stop weights could be placed on links along preferred routes (1). More directly, strictly arterial optimization tools such as PASSER II might be run and implemented on only the preferred arterial routes (2). Although empirical applications of these approaches have been tried, no general strategy for the problem has been developed.

The question of attractive diversion is tied in significantly with questions of traveler response and traveler behavior. Leaving aside the possibility of mode change, attractive diversion should be viewed in context of demand/supply equilibration, a basic component of transportation planning.

Areas of research in this area could include 1) development of methods for selecting preferred routes, 2) implementation and evaluation of experiments in directed and attractive route diversion, in terms of overall network performance, and, 3) development of traffic control logic to provide route diversion in rapid response to incidence occurrences such as accidents or control system malfunctions.

Changeable Message Displays

Changeable message displays perform such functions as prohibiting left-turn movements at certain times of the day, providing route diversion information, and advising of road conditions ahead. Thus, there displays are closely allied with the discussion above as an implementation tool for directed diversions.

Another class of changeable message displays are lane control signals (red and yellow X, green arrow). An example application is assignment of extra lanes to the peak direction of travel (e.g., four lanes inbound, two lanes outbound to and from a CBD in the AM peak hour). Such signals have also been used for high occupancy vehicle lanes.

Lastly, changeable message signs on freeways are important to traffic signal systems as a means to define functional, operational, and visibility requirements of the signs. In particular, freeway signs underscore the need for signs to be highly visible, simple, direct, and timely.

Although research is needed, very little work has taken place in the United States on use of changeable message signs to divert drivers to optimum arterial routes. It is apparent that an extensive arterial or arterial/freeway surveillance system would need to be in place before significant route diversion by message display would be feasible.

Three general types of changeable message signs that provide written information are available for overhead or side-of-road mounting: Rotating drum, bulb matrix, and disk matrix. Rotating drum signs are used where a limited number of sign messages are needed. Such signs are relatively simple to operate and maintain. The bulb matrix sign consists of rows of lights on which an infinite variety of messages can be displayed, by using computer or microprocessor control. This type of sign is highly visible but also has high energy and maintenance costs. The disk matrix sign is the same as the bulb matrix sign except that a series of magnetically controlled, reflective rotating disks replace the light bulbs. This type of sign compared with the bulb matrix sign has lower visibility, similarly high maintenance costs, but reduced energy costs. Fibre optics changeable message signs at present do not appear to have the needed legibility for use on highways.

For use on arterial streets, it is suggested that letters on changeable message signs be at least 10 inches in height. External illumination is required for both the rotating drum and disk matrix signs. In design development of changeable message signs, a strong commitment must be made to optimum levels of sign operation and maintenance.

Turning to the lane control signals, these control devices use both fibre optics and bulb matrix displays. Sometimes such lane control signals are supplemented with simple two-message fold out signs advising drivers in words of allowed lane usage. The costs of installing and maintaining a system of arterial lane control signals are high.

Overall, there is a need to develop strategies and methods for advising motorists on traffic conditions within a travel corridor, based on real-time surveillance data.

Regarding changeable message signs with verbal messages, a need exists for a sign that provides 1) good target value and high legibility, 2) a large number of messages, 3) low initial cost, and 4) low operating and maintenance costs. Guidelines for optimum sign location, frequency or implementation, and content of sign messages are needed as well. Last, research is needed to determine if benefits of changing display aspects exist (e.g., letter height or background color) when sign message changes are made.

With respect to lane control signals, there is a need to reduce initial operating and maintenance costs while still offering safe and efficient traffic control. Some research on implementation of lane control signals to control high-occupancy vehicle traffic is also merited.

RAILROAD COORDINATION AND SPECIAL VEHICLE TREATMENT

Railroad Coordination

Coordination of highway traffic signals with railroads encompasses two basic activities. The first activity involves traffic signal preemption logic and control in the vicinity of a grade crossing when a train is present. The second activity involves at-grade operation of light rail transit (LRT) systems in tandem with highway flow, with an attempt to maximize operational efficiency of both modes. To some degree, these two activities overlap.

Regarding traffic signal control in the vicinity of a grade crossing, the emphasis to date has been on safely clearing out the grade crossing when a freight or passenger train approaches (3 - 5). Little or no work has gone into 1) maximizing parallel highway/railroad flows by extending cross street green time and 2) instituting special recovery algorithms on conflicting highway flows, after the train clears the crossing. Actuated coordinated systems at present handle this latter case to a limited extent. Flexibility in control is important, because long grade-crossing blockages typically lead to significant traffic diversions and changes in flow patterns.

The recommended preemption sequences for clearing a crossing are somewhat arbitrary; they are based on a general rule calling for preemption circuitry when signalized intersections are with 200 feet of a grade crossing that has automatic warning devices. Theoretical and empirical studies focusing on both safety and flow efficiency would permit development of more comprehensive guidelines on the need for, and design of, preemption coordination.

Turning to at-grade LRT operations, traffic control must first address questions of short, frequent blockages of grade crossings, related to the above discussion. In addition, when LRT systems operate on shared highway right-of-way, there is a desire to optimize joint LRT and highway flow in the corridor. In North America, LRT has only recently reappeared on the scene so that control strategies have yet to be developed. Control strategies should be conceptually similar to those for preferential treatment of high-occupancy vehicles. Recent works on this topic have been of a theoretical nature (6 - 8).

Research needs to be conducted into the methods and benefits of special system control strategies in the presence of grade crossing blockages. System control both during grade crossing blockages and afterwards needs to be addressed: during blockages to maximize parallel highway flows and after blockages to recover from the effects of system disruption. Applied research is also needed to deal with alternate preemption and priority treatments for at-grade LRT operations.

Special Vehicle Treatment

The subject of special vehicle treatment, ranging from priority treatment of transit vehicles to preemption treatment of emergency vehicles, is closely related to traffic control for LRT systems, as outlined above. Operating conflicts between competing modes such as ordinary and special vehicles have always existed and have been resolved on the basis of engineering and social considerations.

Considerations in designing a system for special vehicle treatment include 1) the nature of special vehicle arrival patterns, 2) the cost and complexity of needed traffic control equipment, 3) limitations on methods of conveying to drivers that a special vehicle treatment is in effect, and 4) human factor limitations such as expected performance of the traffic control system. Response to a special vehicle occurrence typically contains three elements: transition from normal operation to special vehicle treatment, special vehicle treatment, and transition from special vehicle treatment to normal operation. Microprocessor-based control equipment as well as some solid-state equipment offer the most flexibility in handling the three elements.

Recent discussion within the National Committee on Uniform Traffic Control Devices highlight two types of special vehicle treatments. The first type involves high-priority conflicts between trains, drawbridges, and emergency vehicles and normal highway traffic. In these cases, transition into special vehicle treatment can shorten pedestrian clearance times below normal requirements. The second type of special vehicle treatment involves conflicts between, for example, buses or car pools and normal highway traffic. In these cases, full pedestrian clearance requirements are normally honored. A related concern is the allowed phase sequences for transitioning into special vehicle treatment.

Various signal phasings and displays during special vehicle treatment are possible, involving such aspects as flashing signal operation and all-red indications. As with control strategies for recovering from train blockages of grade crossings, transition from special vehicle treatment to normal signal operation can be complex. As larger areas of influence are considered, systemwide responses are likely to be implemented. Certain types of special vehicle treatments need not have seriously negative impacts in terms of network traffic flow.

Regarding transition into special vehicle treatment, research should focus on the following: warrants for determining the need for system response to a particular class of vehicle, the acceptable limits of system disturbance allowed by the response, and the exact nature of the transition to special vehicle treatment.

Regarding traffic control during special vehicle treatment, research should focus on a) checks for limiting the necessary time and space of the special vehicle treatment and b) on developing the alternate devices or signal displays to communicate to drivers the presence of a special vehicle treatment.

With respect to transition out of special vehicle treatments, there is room for much research into optimum methods either to recover from a special vehicle treatment, or to enhance the impacts of the treatment in a particular way.

DIAMOND INTERCHANGE TRAFFIC SIGNAL CONTROL

The interface between free-flow freeway operation and stop-and-go arterial operations is an important and complex aspect of traffic engineering. In relation to traffic signal systems, freeway interchanges that include traffic signals are of interest. Diamond interchanges are of particular concern because of their frequency across the country and because they are often critical intersections along a signalized arterial.

There are many types of diamond interchanges, including full diamonds, half diamonds, and split diamonds, all with or without frontage roads. About 75% of all diamond interchanges are full diamonds (with or without frontage roads) such as those shown in Figure 3 (9).

Over time, various phasing strategies have evolved for handling diamond interchanges. Figures 4, 5, and 6 illustrate various phasing strategies, all of which have been used for many years. Pretimed, traffic-responsive, and actuated control have all been used for diamond interchanges, depending on the need for system interconnection with adjacent signals and on the variability in traffic demand by time of day and day of week.

Pretimed controllers are most useful when daily traffic patterns are highly predictable. By using two separate controllers for the diamond intersections, additional phasings besides those shown in Figure 4 and 5 can be implemented. This type of control is the cheapest to install and maintain.

Traffic-responsive control has evolved under the California Department of Transportation (Caltrans) by using two California/New York Type 170 controllers for diamond controllers. By using on-street detectors, one of nine preprogrammed phasing patterns is selected and provides phase sequences such as those in Figures 4 and 5, plus slight variations (10).

With respect to actuated control, there are four basic full-actuated designs in use. These are 1) two type 170 or NEMA controllers, operating isolated or co- ordinated, 2) a single type 170 or four-phase NEMA controller, providing the three-phase operation shown in Figures 4, 5) a single four-phase NEMA controller with special features providing the four-phase operation of Figure 6, and 4) a single eight-phase NEMA controller with special features providing either four-phase or three-phase operation, as shown in Figures 6 and 7 (Texas Diamond controller).

The special features of the third type of controller include uses of an overlap card, an external double-clearance interval timer, and detector switching, among others. The Texas Diamond controller uses special internal logic to achieve similar special features for providing the phasing for the third type of control.

Diamond interchange control within a traffic signal system can be oriented to either cross-street or frontage road operations. All of the various controller types described above can be incorporated into coordinated systems by direct interconnect and interface with a control computer or by use of background cycle timers. The Caltrans traffic-responsive design and the Texas Diamond full-actuated controller normally provide the most desirable features for system control, including alternate phase sequencing for optimum interchange and/or progressive flow (11).

Among the important considerations in the planning, design, and operations of diamond interchange control are 1) the need to anticipate traffic growth both in the near future and in a time frame of about 10 years, 2) the possible use of an evaluation program such as PASSER III for analyzing phasing needs, 3) the use of standard plans and designs, and 4) the need for regular checks on performance of current signal timings.

Further research should work to improve traffic control and phasing at diamond interchanges. One specific aspect should be development of a microprocessor to determine maximum timings for individual phases of actuated controllers on a real-time basis.

Related to the above is the need for guidelines on selecting the best type of control at diamond interchanges. On-going work in Texas may satisfactorily meet this need (12); one part of this work involves freeway analysis techniques, including the need to interconnect diamond interchange signals with adjacent traffic signals.

Although not specific to diamond interchange control, research is needed into self-diagnostic and redundant circuitry for traffic signal controllers and detectors. Indications are that the small added initial cost may well be compensated by reduced maintenance and operating costs. Similarly, consideration should be given to developing manuals, training schools, and standard contracts for the maintenance of traffic signal systems.

Figure 3. Types of full diamond interchanges.

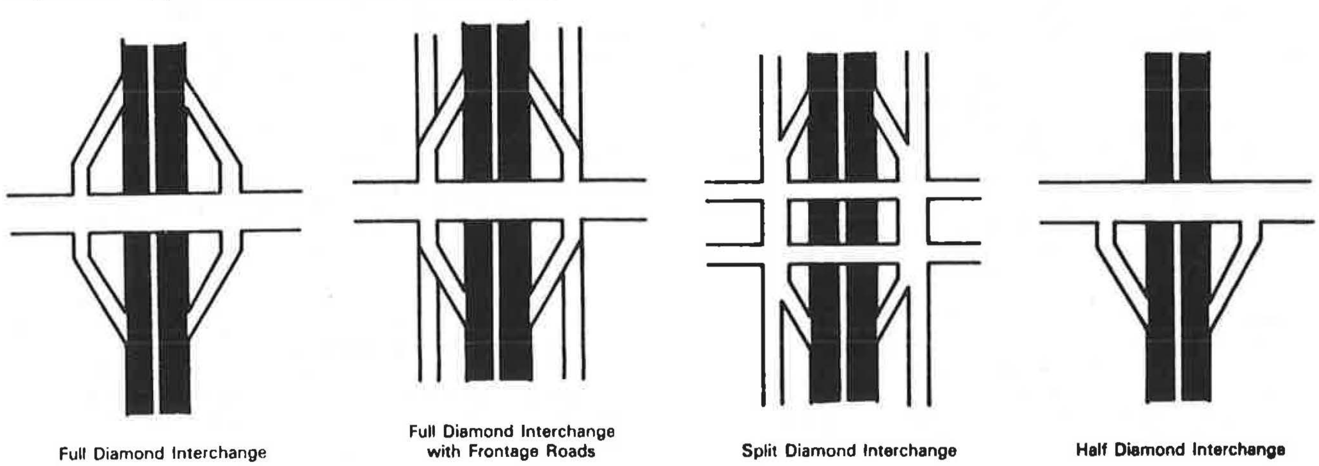
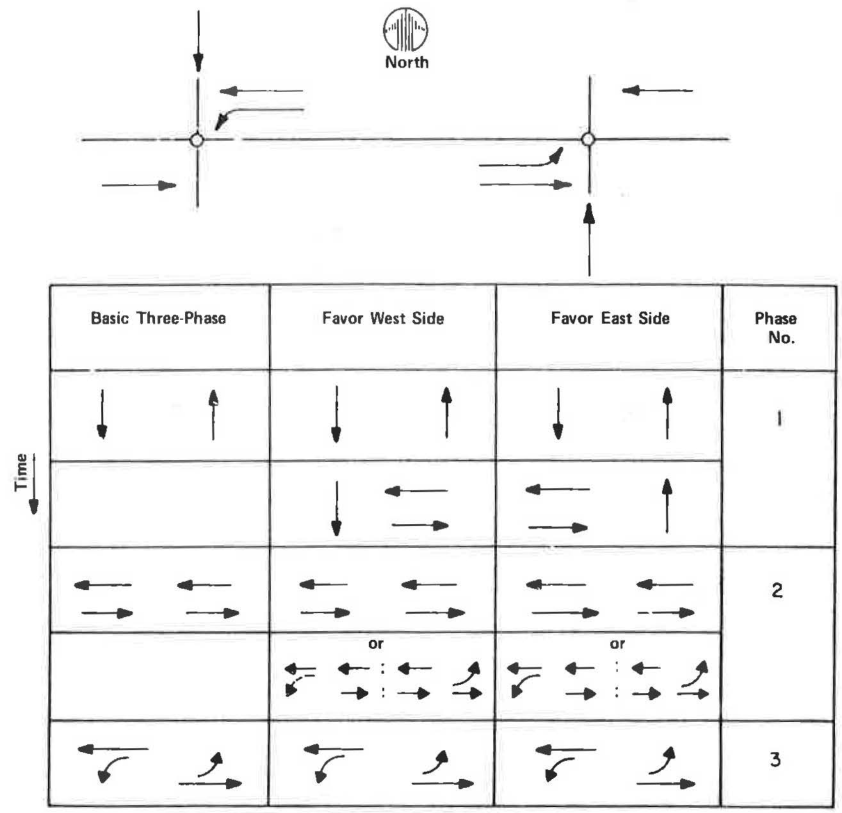


Figure 4. Three-phas‹ pretimed diamond interchange phasing.



Note: Other three phase operations than those shown can be provided under pretimed control through changes in left turn sequences, offsets and splits.

Figure 5. Four-phase pretimed diamond interchange phasing.

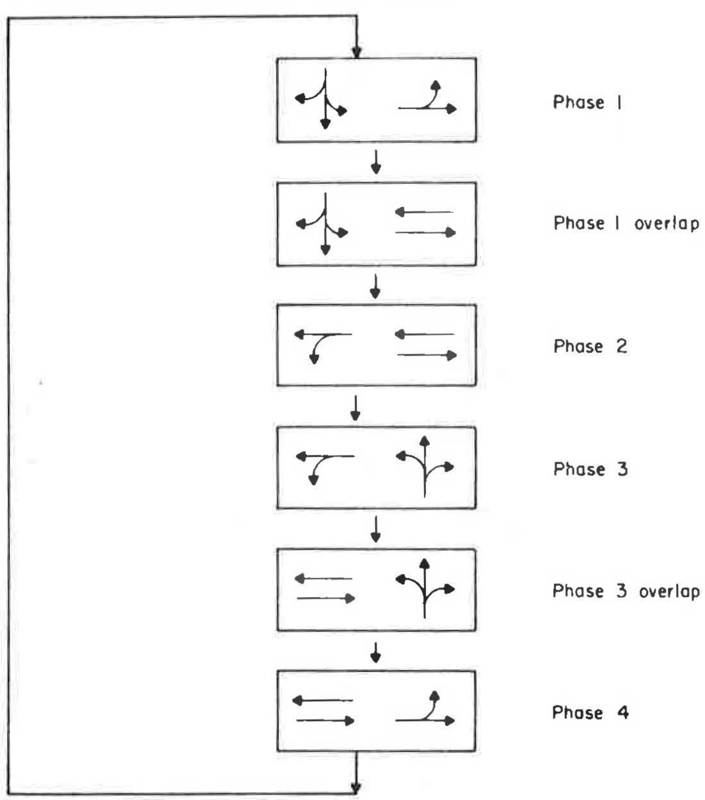


Figure 6. Four-phase full traffic actuated diamond interchange phasing.

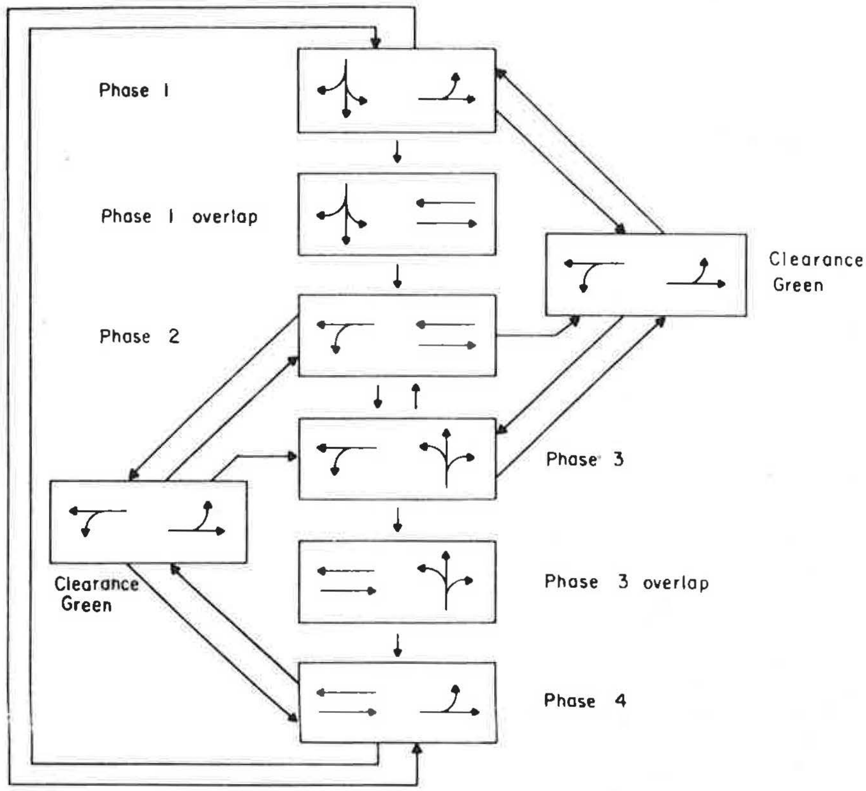
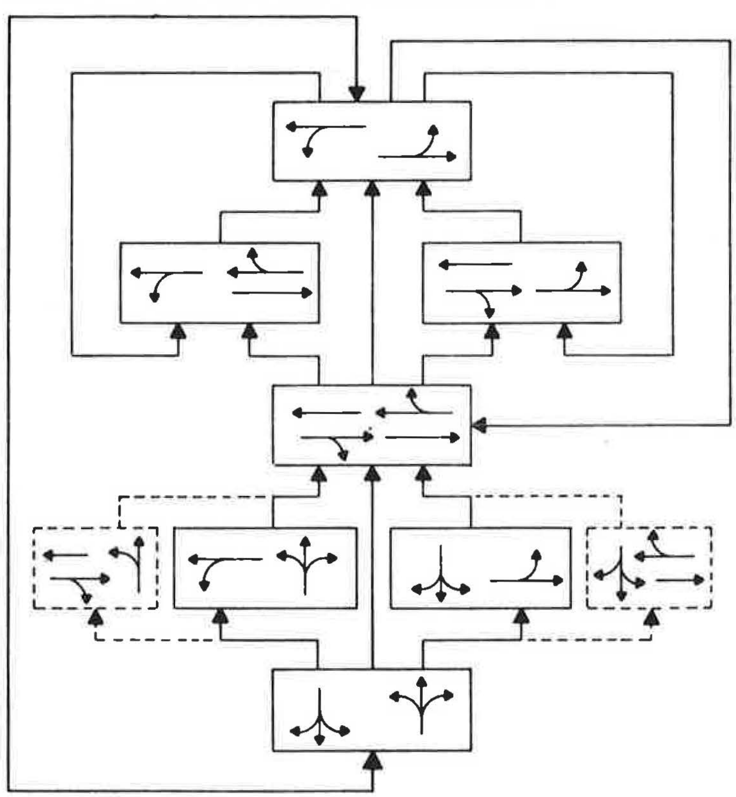


Figure 7. Three-phase full traffic actuated diamond interchange phasing (2).



PEDESTRIAN CONSIDERATIONS IN TRAFFIC SIGNAL SYSTEMS

Pedestrian considerations in traffic signal systems revolve around the basic conflict in all traffic engineering, namely safety versus efficiency. Here, it is the safety of pedestrians in relation to the efficiency of the signal system in moving vehicular traffic. The trade-offs often are difficult.

In addressing pedestrian considerations, it is important to have a good understanding of pedestrian demand in a given study area. Of interest is not only volume of pedestrians by time of day, but also the composition of pedestrian flow (e.g., the number of elderly/handicapped persons who use a crosswalk). Given the demand, it is then fairly easy to compute pedestrian crossing requirements: for example, 5 through 7 second minimum WALK plus flashing DON'T WALK equal to street width divided by four feet per second.

There are a variety of pedestrian phasing techniques, the simplest being to use no pedestrian signal faces but to allow adequate crossing time with the green ball (3, 13). Some data indicate this arrangement is no less safe than locations with pedestrian signal faces (14).

Phasing techniques that use pedestrian signal faces include: 1) concurrent pedestrian/vehicle timing, 2) late or early release of pedestrians, 3) split phasing for crossing of wide streets, with a refuse island in a central median, and 4) exclusive pedestrian phasing in some or all crosswalks (scramble phasing, or "Barnes dance"). Concurrent timing is by far the most prevalent. Scramble phasing is peculiar to a number of metropolitan areas and typically results in longer pedestrian and vehicle delays than other phasing techniques.

A basic operational problem regardless of phasing technique is lack of pedestrian understanding or compliance with pedestrian indications. The clearance function of flashing DON'T WALK and the difference between steady WALK and flashing WALK are examples of commonly misunderstood features. More serious for traffic signal systems is the fact that most pedestrians do not use pedestrian push buttons, (14), detracting from system efficiency and probably safety as well.

Generally speaking, there are two strategies used to handle pedestrian timing requirements in traffic signal systems. Both strategies depend on the existence of pedestrian push buttons throughout the controlled area.

In the pedestrian present strategy, pedestrian demands are assumed to exist for all through phases. Signal timing plans are then developed by using pedestrian crossing requirements for minimum through green times. In the absence of pedestrian calls, excess green time is assigned to one or another signal phase. Overall phase and cycle times are longer under this strategy than would otherwise be the case.

The counter to the first approach is the no pedestrian strategy in which initial signal timings are developed by assuming no pedestrian demands. When an arterial pedestrian call is received, the associated through phase is lengthened accordingly, and other phases are shortened. Sometimes the local controller must be allowed to run free of system control, due to excessive pedestrian demands. Combinations of the two different system control strategies can be expected within the same system.

A theoretical concept with unknown implementations is the minimization of person-delay, including both pedestrian and vehicle occupant delay, in timing for traffic signal networks. Similarly, pedestrian effects need to be considered in estimating vehicle saturation flow values when such values are critical in developing signal timings. The method of assigning excess time to a particular pedestrian phase due to vehicle timing requirements has implications for system hardware and software, in addition to operational efficiency.

Research is needed to develop guidelines covering when to apply pedestrian phasing or control strategies and when to use pedestrian signal heads. Identification of special hardware and software accommodations required by pedestrian operations would also be useful.

Research is needed to identify the benefits of more comprehensive surveys of pedestrian demand, by time of day and pedestrian classification.

Work is justified into the theory and application of person-delay minimization, based on pedestrians and vehicle occupants, as opposed to vehicle-delay minimization only. Further work may be useful regarding vehicle saturation flow adjustments due to pedestrian/vehicle interactions.

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CHAPTER SIX

TRAFFIC PATTERN DEVELOPMENT AND SYSTEM ANALYSIS

MEASURES OF EFFECTIVENESS

Often, whether one control scheme is judged better than another depends on what measure of effectiveness is used. In this context, only the traffic performance aspects will be covered here and not the control system performance (e.g., cost, reliability, features and functions).

The importance of the measure of performance can pe illustrated by a simple example: an isolated two phase pretimed signalized intersection. If delay is the measure and if the flows are fixed, then an optimum cycle length exists. A longer or shorter cycle length than this optimum will produce larger delays. Note, however, that almost all traffic must stop before entering the intersection (typically about 80%). If, on the other hand, the number of stops is the measure, then the best strategy is to give a constant green to the direction that has the heavier traffic. All the traffic on the minor approach stops, but none stops on the major approach. At least half of the traffic, then, does not stop. Any other strategy results in more stops. Of course, this strategy would never be used in practice, because the delays on the minor approach grow to infinity.

This example shows that the strategies used to minimize delays and to minimize stops are completely different. Another difficulty is that of completely defining the measure used. For instance, if fuel use is the measure in the above example, then a cycle length slightly longer than the minimum delay cycle length is typically best. But note that in this example flows are fixed. If flows are allowed to vary as drivers make their decisions based on traffic conditions, then the strategy that minimizes fuel use is to close the intersection completely so no one will use it. However impractical this solution, it does indeed give the minimum fuel use at the intersection if flows are allowed to vary. Obviously, regardless of the measure used, more conditions must be imposed when flows are allowed to vary.

Important Early Works

There are many items in the literature that are considered important works that any researcher should review for an adequate perspective on traffic performance measures of effectiveness.

In 1929, Matson (1) gave methods of calculating delays at an isolated signal. He also discussed schemes for coordinating arterial signal systems. Since that time, bandwidth has been the most common measure of the quality of coordination. Bandwidth will be discussed later.

Important work in the 1950s includes that of Rothrock and Keefer (2, 3), Saal (4), Berry and VanTil (5), Hall and George (6), and May and Wagner (7). These papers dealt primarily with methods of finding the travel time and/or average travel speeds on signalized arterials and at intersections, although limited attention was given to speed changes or stops and delay times. Most involved the use of floating car studies, usually in straight trips up and down arterials. Saal (4), and May and Wagner (7) also measured fuel use in the test cars.

Later May developed an interrelationship among average speed, running speed, stopped time, and fuel economy. He also explicitly considered safety and road user costs, along with the traffic flow variables, in a formulation of quality of flow expressed in dollars.

The Bureau of Public Roads Study of Wisconsin Ave. (8) explored the many kinds of impedances to flow on an urban arterial.

In the 1960s and early 1970s, traffic simulation computer models emerged. Examples include Webster (9), Gerlough (10), Wardrop (11), Robertson (12), Wagner (13, 14), and Lieberman (15). Resulting models included TRANS, SIGOP, UTCS-1 (later NETSIM), and TRANSYT. Each produces tables of traffic performance, although the same measures are not used throughout nor are the same measures always defined similarly.

Other concepts were introduced: Greenshields (16) developed a driveometer that measured rates of speed changes and direction changes. He also pioneered work in using galvanic skin response to measure driver tension in urban traffic. Cooper and Walinchus (17) suggested using vehicle miles of travel (VMT) travel time and a newly defined energy ratio = (Average Speed/Cruise Speed)^2, which indicates the roughness of flow.

In the early 1970s, Evans (18) and his colleagues investigated the relationship between fuel and various traffic flow variables. They have shown that overall travel time and stops explain most fuel use in urban traffic. The finding that stops are an important determinant of fuel consumption was confirmed by Wagner (19).

In the mid to late 1970s, the coming of multimodal transportation system management broadened the perspective on measures of performance. Abrams (20) suggested using travel time, traffic volume, vehicle occupancy, and transit passengers to derive VMT, PMT, VH of delay, VHT, PHT, transit PMT, emissions, and energy.

Bandwidth

Manual timing techniques for arterial signal systems have used bandwidth almost from the beginning of the use of coordinated signals in the 1920s. The technique has the advantages of being easy to learn and of giving visually satisfying solutions. Its major drawback, as has been pointed out many times [see, for instance, Newell (21)], is that it deals with a geometric quantity, bandwidth, which has no demonstrated or necessary relationship with delay, stops, or fuel use. Nevertheless, good field experience has been reported with bandwidth solutions.

The manual technique based on bandwidth is commonly used and is discussed in many sources. For an example, see Baerwald (22). There are at least two computer techniques based on bandwidth, MAXBAND (23) and PASSER II (24).

Equity

One criterion often used by signal timing engineers is that vehicles on different paths should not encounter widely different quality of flow. For instance, it is argued that drivers traveling in opposite directions on a two-way street that has approximately balanced flow should have the same delay, stops, etc.

When only average measures of performance are optimized, the measures experienced by individual vehicles can vary widely. If equity is imposed on the problem, the average measure may worsen somewhat.

Current Works

PRC Voorhees (25), under sponsorship of FHWA, is conducting a study titled Quality of Flow on Urban Arterials. For the study of arterial capacity and quality of flow they are strongly recommending a single measure, average speed, with the stipulations that the type of arterial (particularly its typical cruise speed) be taken into account. More detailed assessments may require other measures.

The Voorhees work and its contemporaries raise numerous issues:

- Can traffic performance quality be measured with a single MOE? If not, how many should be used?
- What measures should be used? Candidates include:
  1. Travel time
  2. Average travel speed
  3. Speed changes
  4. Stops
  5. Delay
  6. Fuel
  7. Stopped time
  8. Driver tension
  9. Energy ratio
  10. Person delay
  11. Vehicle miles traveled
  12. Person miles traveled
  13. Bandwidth
  14. Equity
- At what level should measures be summarized (individual link, intersection, street by street, subnetwork, total network)?
- How can traffic performance best be sampled? What about side roads and turns, complex routes versus straight trips up and down arterials?
- What is known about the effect of signal system performance on the safety of urban streets? Knowledge here could produce large benefits.
- How should fuel use, emissions, and road user costs be modeled? Existing procedures vary. Rapidly changing automobile fleet mix and trucks complicate the issue.
- Can the public detect improvements in the quality of flow? To what measure is the public most sensitive? How can communications with the public improve?
- What roles should models and field studies play in evaluating performance? Do traffic engineers tend to be critical of models and ignore the shortcomings of field data (sample size, representativeness, measurement errors, and uncontrolled factors)?

Although many aspects of measures of effectiveness have been discussed here, they form only part of an attempt to foster the proper consideration of objective and relevant MOEs (and good methodologies) as an integral part of a general thrust to improve the understanding of and practice of traffic signal system planning, design, development, implementation, and operational management and maintenance.

MANUAL VERSUS COMPUTER-DERIVED SIGNAL TIMING

As computer-derived signal timing methods have been. developed, there seems to have been a stagnation in the development of manual timing methods. This is unfortunate for several reasons. It will be shown later that manual techniques can, for some signal systems, provide timing schemes that rival computerized schemes in effectiveness. The application of manual techniques by the signal timing engineer does not require the availability of a computer nor the coding of networks. Considering the budget and institutional constraints of many cities, counties, and states, it is probably unreasonable to expect that computers will be available on a wide scale to perform traffic engineering tasks for many years, if ever. For many signal timing engineers, the use of a computer is a forbidding task. This makes the further development of manual techniques necessary to the profession.

Furthermore, there is some knowledge about signal systems that can only be gained by studying manual techniques. Computerized schemes show the best solution, but have no way of displaying any fundamental principles that make that solution the best nor can they show related solutions that are also good.

Cross-pollination of Manual and Computer Techniques

Computer models can be used to help improve manual timing techniques. Optimizing models are particularly useful for this, because the network or traffic patterns can be changed at will and the model will determine the best timings, shortcutting the optimization step.

On the other hand, computer model analysis procedures could benefit from knowledge derived from manual techniques. Signal timing optimization techniques at present try many solutions that are clearly inferior before finding a good solution. By their nature, manual techniques cannot afford to even consider unwise potential solutions; they must be restricted to considering a small family of possibilities. The introduction of such logic into computer models could conceivably make them quicker and, in the cases of those models that find only a local optimum, the model could be made to find a solution closer to the global optimum as well.

Delay, Stop, and Fuel-Based Manual Methods

Measures of effectiveness for arterial signal timing were discussed previously in this chapter. There it was concluded that delay, stops, or fuel use (or a combination) is probably better than bandwidth as a measure of effectiveness, because they measure quantities that are of physical significance on the street.

Nevertheless, no generally applicable or acceptable manual procedure that is delay-stops-fuel-based has yet to be developed. Procedures developed by Newell (21, 26) are limited to very light or heavy traffic flow. He points out that the problem of intermediate traffic flows is difficult because the traffic pattern at an intersection depends not only on the signal timing at the adjacent intersections but also on the timing at intersections further removed. This interdependence complicates the flow patterns at each signal such that direct analysis is almost hopeless.

This is where computer methods can prove helpful. Most often, they have been used to derive desired signal timing plans directly. It is instructive, however, to use computer models instead to test for patterns produced when controlled changes are made in the network and the flows. Then, if the pattern that would be produced for a particular problem can be predicted, the problem would be solved, albeit indirectly.

Note that this approach is similar to that used in other areas of engineering design, wherein problems are solved for many specific cases, and the practitioner simply looks up the right answer in a handbook.

Of course, the development of the patterns applicable to various networks and flows would require access to a computer. After the patterns were developed, however, the matching of a pattern to a particular physical problem could be done by hand. In this way, the analysis of patterns produced by computer models could become the basis for an improved delay, stop, and fuel-based manual signal timing technique.

Preliminary indications are that this technique will provide answers sufficiently different from bandwidth techniques that some major rethinking and relearning will be required. Evidence can be found in the comments of signal timing engineers to timing plans produced by delay, stop, and fuel-based models. Usually these models produce no through bands, and the usual reaction is that the model must be in error. It is not the model that is in error, however, it is the intuitive feeling that through bands should be produced.

Newell (21) showed that, for heavy traffic on two-way streets with unimpeded travel times between signals of greater than about 1/2 the cycle length, the offsets between adjacent signals should be set to plus or minus the unimpeded travel time. (Such plans will be called members of the one-way family.) For instance, if all the offsets were positive, this would be a one-way progression. If the signs of the offsets alternated, then it would be what might be called an alternating one-way pattern. Logically, if the traffic in one direction is measurably heavier than the other, or if there are fewer turns, then the direction that has the higher flows and fewer turns should be progressed.

Shanteau (26) used TRANSYT-7F to test this hypothesis under a wide range of flows and turning percentages. Only with heavy turns (over about 30%) and light flows (less than about 30% of capacity) is the optimal solution not approximately a member of the one-way family. There were some small variations in the pattern, presumably produced by the spreading of the platoons, but the difference in the performance indices of the one-way solution and the solution chosen by the model are inconsequential and probably too small to measure in the field. Such accuracy from such a simple rule of thumb is a pleasant surprise. One would hope that other advances in manual techniques would give similarly good results.

Such discoveries could lead to new computer models. If it is known that the timing pattern for a two-way street will be a member of the one-way family, then it would be easier to investigate the effects of changing cycle lengths than would be otherwise. A delay, stop, and fuel-based model could include logic that easily allowed it to optimize cycle lengths as well as splits and offsets.

Researchers working on manual and computer-derived signal timing methods need not be adversaries. By working together, each can use information from the other to improve the end product. The most difficult job, however, may not be in getting the researchers to work together nor may it be in the development of improved procedures. The major problem will probably be in weaning signal timing engineers away from bandwidth-based methods and turning them toward delay, stop, and fuel-based procedures instead.

SIMULATION AND OPTIMIZATION MODELS

This section summarizes the function, input/output requirements, advantages, and limitations of a limited number of operational models that simulate traffic flow on arterials and networks. The models described are those that seem to be most widely used at this time. More information on these and other models, including some now under development, can be found elsewhere (28-31). Outside the scope of this section are freeway corridor models or models limited to isolated intersection analysis.

The order of presentation follows the sequence: macroscopic/linear arterial models, macroscopic/network models, and microscopic network models.

SOAP

SOAP (32) is a macroscopic analysis with the primary objective of developing signal control plans for individual intersections. It is also capable of analyzing progression delay.

SOAP can analyze up to 48 time periods of from 5 to 60 minutes each. Only one intersection is simulated per run (isolated intersection case) or the intersection of interest plus the four approach links from the surrounding intersections (progression case). Inputs include traffic flows per approach, truck and bus composition, left turn data, signal related data, saturation flow rates, and progression-related data. Basic outputs include delay, percent saturation, maximum queue, percent stops, excess fuel, and left-turn conflicts. More are available on request.

Program documentation is well written and the program is easy to use. Disadvantages include: incapability of analyzing closed loops, lack of widespread testing, and lack of validation of the platoon dispersion algorithm.

MAXBAND

MAXBAND (33) is a bandwidth optimization program that calculates signal settings on arterials and triangular networks. The program produces cycle lengths, offsets, speeds, and phased sequencing to maximize a weighted sum of bandwidths. As many as 12 signals can be handled efficiently.

Basic inputs include the range of cycle lengths, network geometry, traffic flows, saturation flows, left-turn patterns, queue clearance times, and range of speeds. Outputs include a data summary report and a solution report that contains cycle time and bandwidths, selected phase sequencing splits, offsets, and travel times and speed on links.

The main advantage is the freedom to provide a range for the cycle time and speed. The main disadvantage is its use of bandwidth as its optimization criterion. Other disadvantages include the limited experience with field testing and the lack of incorporated bus flows in the optimization.

PASSER II-80

PASSER II-80 (34) is a bandwidth optimization program that calculates signal timings on linear arterials. The program uses a fixed-time scan search to produce the cycle length, phase sequencing, splits, offsets, and band speed that maximize bandwidth in both directions for up to 20 intersections. A modified version of Webster's delay equation is used to approximate platoon effects.

Basic inputs include the range of cycle lengths, movement flows, saturation flows, left-turn patterns, queue clearance times, desired speeds, minimum green times, allocation of bandwidth by direction, cross street phase sequences, and intersection distances. Outputs include cycle length, bandwidths, band speeds, a time-space diagram, delay, probability of queue clearances, offsets, splits, phase sequences, and volume-to-capacity ratios.

Its main advantage is its flexibility to vary cycle length and band speed and its ability to consider multiphase operation under a variety of sequencing strategies. Other advantages are ease of input and low run times. The main disadvantage is its use of bandwidth as its optimization criterion. Also, it does not accommodate closed networks, and fuel consumption and emissions are not included.

PASSER III

PASSER III (35) produces the cycle length, splits, and phasing sequence for a pretimed diamond interchange that minimize average delay per vehicle, using a macroscopic, deterministic time scan optimization. It can also determine splits and offsets for interchange signals along a frontage road, using a bandwidth procedure.

Inputs in addition to those required for PASSER II-80 include the interchange description for the isolated case and interchange spacing and progression speed for the progression case. Outputs include signal settings plus values for delay, degree of saturation, etc. For the progression case, bandwidth, speeds, efficiency, and time-space diagrams are provided. The main disadvantage is its use of bandwidth as the progression criterion.

SIGOP

SIGOP (36) produces the cycle length, splits, and offsets of signals in a grid network that minimize a delay disutility function by using a macroscopic traffic flow model. It can handle up to 150 intersections.

Inputs include arrival flows and saturation flows (in terms of headways), minimum green times, yellow times, special phase times, and passenger car equivalent factors for trucks, buses, and turning vehicles. Outputs include time-space plots along selected arterials and link statistics.

One advantage is that multiphase signals can be modeled. Disadvantages include run times for large networks that are no shorter than other programs, and SIGOP III (the latest version) lacks extensive field testing.

TRANSYT

TRANSYT produces splits and offsets for signals in a network that minimize a performance index by using a hill climbing procedure and a macroscopic, deterministic flow model. Its dimensions are usually set to handle up to 50 intersections and 300 links. Numerous versions of the program have been produced, both by its originator and others. In most versions, the performance index is a user-specified balance between delay and stops. Phasing and cycle length are not optimized in most versions.

Basic inputs include cycle length, phasing, performance index weights, lost time, link lengths, either link travel times or speeds, link flows, turning movements and saturation flows. Basic link outputs include percent saturation, total travel, travel time, delay, rate of stops, maximum queue lengths, offsets and splits. Network outputs include similar statistics plus the value of the performance index.

Various versions of TRANSYT incorporate different improvements, TRANSYT-6C (37) includes fuel consumption and emissions estimates, demand response, a provision for priority links, and a more comprehensive performance index. The user may specify optimization based on weightings of stops, delay, fuel consumption for both priority and non-priority vehicles, and carbon monoxide, nitrous oxides, and hydrocarbon emissions.

TRANSYT-7F (38) uses North American nomenclature on input and output (rather than English). It also produces a time-space plot and estimates of fuel consumption. A new revision will optimize cycle lengths and identify potential intersection blockages.

TRANSYT-8 (39) incorporates gap-acceptance functions for left turns and a cycle search routine. The government of Great Britain charges a license fee, limiting the program's use in this country.

TRANSYT's main advantage is that it uses a fairly realistic flow model without requiring outrageous run times. The main disadvantage is that the hill-climbing algorithm does not find the true optimum.

NETSIM

NETSIM (40) produces the performance of a network by using a microscopic, probabilistic model that incorporates car-following, queue-discharge, and lane-switching algorithoms. It usually has dimensions to handle 99 intersections, 160 links, and 1600 vehicles (at one time).

Inputs include network geometry, flows, saturation flows, turning counts, traffic composition, and signal settings. Outputs include a variety of measures such as delay, stops, cycle failures (for pretimed signals), fuel consumption and emissions.

A major advantage is its ability to simulate control strategies other programs cannot, such as STOP, YIELD, pretimed, and actuated control. Bus operations and pedestrians can also be modeled. The major disadvantage is that it is a simulation only, no optimization is performed. At that, run times tend to be long. Also, the quality of documentation is spotty and the model cannot, in its present version, model coordinated actuated dual ring controllers (a revision to do this will be published).

NETSIM/BPS

NETSIM/BPS is a modified version of NETSIM that simulates bus preemption for nearside or farside stops at pretimed signals. Strategies modeled include green extension, red truncation, cycle-skipping and cross street/main street preemption selection.

Inputs include the NETSIM input plus green extension and red truncation durations, detector surveillance data, and bus trace parameters. Outputs include the NETSIM measures.

This program shares NETSIM's advantages and disadvantages, with the addition that this program lacks the ability to simulate preemption with actuated controllers.

Discussion

The state of the art of each of the programs discussed above is advancing rapidly. Search schemes are improved, capability and outputs are added, and optimization flexibility is enhanced continually; however, significant voids exist.

One need is the determination of optimal signal settings for actuated controllers in a network. Recent papers have reported on the estimation of delay at actuated signals. The next logical step is the development of models that provide the data needed to minimize delay.

Another problem sometimes experienced is discrepancy in values of MOEs estimated by different models. There are two potential causes of this problem: 1) the user has insufficient training and/or experience, and 2) problems within the models. Concerning the latter, most all models are validated. Yet published reports give insufficient details to judge the quality of the validation. Further, if the validations were adequate, the models should give the same results for a given situation. Perhaps the reason is that field measurements are so difficult to perform. Nevertheless, a user who obtains different results from different programs may lose confidence in one or both of them. In general, models should be better validated and these validations should be better documented. Finally, the models are not widely used by many individuals in the traffic engineering community. The causes are the lack of availability of computers and the wide variation in technical expertise of signal timing personnel. Even as computers become more available, it is by no means assured that significant increases in use will follow. It matters not how sophisticated the simulation and optimization models are if they are not used by individuals in the field.

The publication of a simulation periodical would keep the user community informed of model development, testing, usage and revision. For instance, such a publication would prove helpful in keeping up with the many outwardly similar, but internally different versions of NETSIM. An example of this type now defunct is the FREQ/TRANSYT Bulletin.

MICROCOMPUTER SYSTEMS IN TRAFFIC CONTROL

Definition and Scope

This section reviews some of the existing applications and identifies others that will emerge in the near future. The hardware systems within the scope of this discussion include, typically, general purpose microcomputers with at least 64 K bytes of memory, at least one floppy disk drive, and a printer. A variety of peripheral and interface equipment might also be involved. Excluded are dedicated process control hardware such as signal controllers, and larger-scale minicomputer and mainframe systems. Examples of more popular microcomputer systems include APPLE, Radio Shack, Xerox, and IBM (Personal Computer). This type of system is of interest to the traffic engineer because its cost is generally well within the budget of a traffic engineering agency.

The applications to be examined fall into the following five areas:

- Engineering calculations
- Data base management
- Intelligent terminals
- Traffic studies
- Process control

The current state of the art and potential advancements will be considered for each of these areas.

Engineering Calculations

Optimization of traffic signal operations requires some computer support. The microcomputer system is used in three ways here.

1. Traditional mainframe computer programs such as TRANSYT and PASSER II have been converted for use on small microcomputers. These are now available commercially.

2. Special microcomputer programs have been written for capacity analysis signal timing, progression design, etc. Some are available commercially and some are public domain programs.

3. Other engineering calculations are performed routinely by small, often specially written, programs.

In all these applications, the microcomputer is simply used as a desk-top calculating machine. Numbers are fed in and results are generated. The advantages include accessibility and interactive data entry. The main disadvantage is that the speed of computation is usually significantly, and sometimes painfully, slower than with the larger systems.

Data Base Management

Several commercial data base systems are now available for signal system applications. Among the most popular are DBASE II (CPM) and DBMASTER (APPLE). Their data base management capabilities (search, sort, merge) and their report generation capabilities are impressive. Cities have already begun to use these capabilities for signal system inventories and maintenance records. There is good potential for use in the management of traffic operational data bases for signal systems. The FHWA has already initiated a project to develop a microcomputer data base for traffic engineering data needed for design and evaluation of signal system operations.

Intelligent Terminals

The microcomputer has vastly expanded to capabilities for remote terminals that communicate with larger computers. Intelligent terminals, unlike their predecessors, offer the ability to transfer and store large blocks of data to do computations on this data and to display the results in numerical or graphical form.

The most important applications of intelligent terminals to traffic signal systems include:

1. Monitoring the operation of a computerized system and generating status reports interactively (41); 2. Transmitting signal operating parameters to local or submaster controllers in the field (42); 3. Interactive data entry for mainframe signal optimization programs such as PASSER II and TRANSYT (43); and 4. Graphic displays of the results of these programs to enhance the traffic engineer's understanding of the system operation (44).

Graphical outputs are likely to become more common in the future because of the capabilities of these microcomputer systems. ^f particular interest is the compatibility of many systems with standard color television monitors. This creates the potential of public displays of areawide traffic conditions through commercial cable TV channels. It also establishes the large-screen projection TV monitor as an excellent central signal system control room display.

Traffic Studies

Signal systems require large quantities of field data for design and evaluation. The ability of the microcomputer system to automate the collection and analysis of these data has already been demonstrated in several systems, including turning movement counts (45), road tube counts (46), intersection delay studies (47), spot speed studies (48) and moving vehicle studies (49). In each application, data collected in the field by using external equipment are read into the microcomputer by using standard serial data transmission techniques. The data are then analyzed and reports are generated automatically. At least seven different types of data collection equipment now feature automatic data transfer.

Soon linkages may be established between these data collection programs and other applications such as signal timing calculations and signal system data bases.

Process Control

Can a small, general-purpose microcomputer system really be used as the master controller for real-time control of a group of intersections? These systems have already been introduced into the market (50). If they are successful, we can expect to see substantial competition in this area, and a large variety of systems become available.

Another process control area is in the signal maintenance shop. A system is currently under development that will do a standardized series of tests in real time on a signal controller to determine how well the controller meets specified functional requirements (51). A separate system, in operation for three years, provides vehicle detection inputs to a controller and monitors the outputs, generating displays of simulated traffic on a video screen (52).

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CHAPTER SEVEN

PUBLIC/PROFESSIONAL COMMUNICATION

During the 1981 ITE meeting, a separate seminar was conducted on the future role of the urban traffic engineer. Several thoughtful papers were presented on current transportation problems. Significant issues of concern to traffic engineers include the following.

1. Demand for transportation facilities and services is increasing the needs of surface transportation.
2. Most personal travel is still by private automobile and is expected to remain so in the future.
3. Personal vehicles are getting smaller, commodity vehicles are getting bigger.
4. Road and street maintenance is not keeping pace with wear.
5. The public has the impression that roads and bridges will last forever.
6. Maintenance of the Interstate System will cost as much or more than the original construction.
7. Substantive provisions have not been made for maintenance or operation of existing facilities.
8. Investment of highway funds is eaten up by inflation.
9. Civil engineering graduates are decreasing in numbers because career outlooks are more promising in other disciplines.
10. Government demand for new civil engineering graduates appears to be decreasing.
11. As governments consolidate and cut back on transportation investments, the position of traffic engineers is often adversely affected.
12. Distrust of science and engineering is growing as an aftereffect of well-meant efforts by various action groups, the news media, and courts.

Many of these issues, especially those related to funding, have become more critical since the ITE meeting.

It is outside the scope of this section to describe a detailed method for developing a public relations infrastructure. Material on the subject is already available. A good report, "Local Public Relations in Transportation Matters," was published by ITE and should be read. Work is also underway by ITE's Communications Committee on Bridging the Gap to Public Understanding. Many in the traffic engineering community may be unaware of these activities.

APPENDIX

Many of the summary papers prepared by the members of the Transportation Research Board Committee on Traffic Signal Systems included suggestions for research and development work in the future. These are listed below as additional information to others in the field of traffic signal system research and development.

1. Designate an agency or committee to serve as a clearing house to assemble representative plans and specifications for use as typical references to assist engineers in preparing their own plans and specifications;
2. Compile a compendium of agencies experienced in procuring and installing network control systems under various techniques;
3. Develop system acquisition procedures that provide for initial competitive selection and negotiated expansion upgrading to aid the development of a standardized evaluation process/procedure;
4. Develop a series of programs for routine analysis of traffic data obtained by a traffic-responsive signal system;
5. Develop an inspectors manual for use during installation of traffic signal systems;
6. Develop a maintenance manual for traffic signal system equipment;
7. Develop guidelines or specifications on maintenance contracts;
8. Develop a training/certification program for maintenance personnel;
9. Develop a series of programs for use in maintenance management (i.e., schedule maintenance, justify personnel requirements);
10. Keep abreast of all ongoing research in systems development and share development results;
11. Identify the research need to enhance the compatibility between the development of signal control technologies and the implementation capabilities of those agencies that have primary responsibility in signal control. This would apply to small cities as well as large cities;
12. Establish a profile of signal control practices and needs for small urban areas;
13. Conduct research on arterial systems. (Most research work to date appears to have centered on CBD networks. The research work should include the investigation of simpler, less-expensive systems.)
14. Begin a long-term cooperative arrangement between government and industry; (SCOOT in England represented the culmination of a long-term cooperative arrangement between government and industry; perhaps a similar venture in the United States would lead to a leap in control strategy development.) Establish one or more facilities in which new traffic control strategies can be tested, improved and further developed based on actual field performance evaluations;
15. Develop schools on the use of computer models such as NETSIM, SOAP, TEXAS, and PASSER, as has been done with the TRANSYT-7F computer model;
16. Publish, on a regular basis, a newsletter on simulation and optimization computer models that would keep the user informed as to model development, testing, usage, and revision;
17. Analyze and resolve to a reasonable degree the differences in measures of effectiveness between various simulation models;
18. Evaluate the effects of various local and master controllers on systems performance; (All signal optimization models are now based on pretimed control. The differences in systems performance between use of pretimed and full-actuated controllers when interconnected to a master controller are unknown.)
19. Develop a microscopic optimization model involving traffic-actuated control;
20. Develop a strategy for designing combined signal system and signing operations so as to accommodate conflicting directional flow along the various corridors which fall within the signalized network;
21. Develop and report on methods designed to assess the impact of using route diversion to improve the overall performance of a complex signalized network;
22. Develop a response logic for distributing directional flow onto two or more parallel routes when emergency conditions arise;
23. More states and cities should be made familiar with the speed funnel techniques and encouraged to use them;
24. Form a task group to establish the functional requirements for use of (home-type) microcomputers for detection, communication control, and displays;
25. Develop self-diagnostics and redundant circuitry for traffic signal intersection controller and detectors;
26. Develop improved freeway diamond traffic control operation such as the use of a microprocessor unit to determine maximum phase times for full-actuated controllers;
27. Develop guidelines for determining the type of traffic signal controller to install at diamond interchanges;
28. Conduct a survey of cities with traffic signal systems to identify their methods of handling pedestrians (of major interest are pedestrian phasings and pedestrian control strategies -- ped present, no ped, use of ped omit, or other); develop guidelines to determine when to apply particular phasing or control strategies; identify special hardware/software accommodations required by pedestrian operations and determine whether pedestrian phasing or control strategies can be modified to simplify the hardware/software;
29. Develop research into the theory and applications of person-delay minimization versus vehicle-delay minimization; determine the effectiveness of person-delay minimization;
30. Investigate methods to determine the effects of pedestrian movements on vehicle capacity in relation to signal plan dqvelopment; if needed, develop guidelines to capacity/saturation flow adjustments due to pedestrian interactions;
31. Develop warrants on the need for system response to a particular class of special vehicle (e.g., train, emergency vehicle);
32. Develop the acceptable limits of system disturbance in reacting to a particular class of special vehicle (e.g., train emergency vehicle).
33. Investigate the potential benefits of demand-responsive traffic control and develop those strategies that offer the most promising results.