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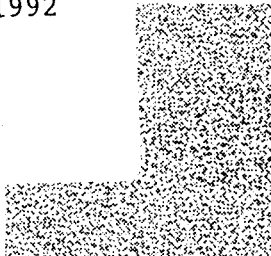
UNIVERSITY OF MINNESOTA

**DEVELOPMENT AND
APPLICATION OF ON-LINE
STRATEGIES FOR
INTERSECTION CONTROL,
PHASE I**

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**Sponsored by:
Center for Transportation Studies**

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**DEVELOPMENT AND APPLICATION OF ON-LINE STRATEGIES
FOR INTERSECTION CONTROL**

PHASE I: REVIEW OF ADVANCED CONTROL STRATEGIES

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December 1992

*The financial support of oil overcharge funds
distributed through the Minnesota Department of
Administration is acknowledged, but the authors assume
complete responsibility for the contents herein.*

University of Minnesota

ABSTRACT

SCOOT, SCATS, PRODYN and OPAC represent the state-of-the-art control strategies for signalized traffic network management by employing advanced control concept such as demand-responsive, on-line timing generation with adaptive features. While there have been individual tests of the above state-of-the-art control strategies by various agencies, no comprehensive effort has been made to evaluate and quantify the performance of each strategy, especially in terms of their applicability to both loops and video detection. This research reviews the advanced intersection control strategies developed to date. Due to the lack of field evaluation that can directly compare each control strategy, this study focused on the theoretical principles and implementation issues found from the literature. Further, the existing intersection control systems in three major cities in the U.S. and Canada are analyzed and their control algorithms are introduced. Finally, the current status of the video detection development is also reviewed.

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I. INTRODUCTION

I.1 Problem statement

Designing and implementing the best signal control strategies that can minimize delays in traffic networks is a key element in managing urban congestion and improving the living environment of urban areas. Currently, most traffic agencies in the U.S. determine the signal timing plan off-line by using arterial or network optimization software. The resulting timing plan is then stored in the computer's memory for implementation by various on-line criteria. The computer models used for this type of control include TRANSYT7F, NETSIM, SIGOP and AAP. More recently, traffic demand-responsive control strategies with on-line timing generators and adaptive control features have been introduced. The latter type of control is represented by SCOOT, SCATS, PRODYNE and OPAC.

While the importance of on-line, demand-responsive intersection control is growing, no comprehensive effort has been made to quantify and evaluate the performance of the real-time, intersection control software developed to date. Further, the applicability and potential benefit of video detection to demand-responsive intersection control has not been fully addressed. Analyzing the advantages and limitations of current state-of-the-art intersection control software is of critical importance in developing advanced traffic management /control strategies that can take advantage of available detection systems including loops and videos.

I.2 Research objectives

The ultimate goal of this research is the development and application of on-line optimal control strategies for intersections and arterials using available data collection systems including loops and video. The main objective of the current project, which is Phase I, is the analysis of the advanced control strategies developed for real-time, demand-responsive intersection control. The results from this research will directly contribute to the design of the best signal timing plans for intersection control. The major accomplishments of the current research will be:

- Analysis and comparison of the state-of-the-art real-time, demand-responsive intersection control software including SCOOT, SCATS, PRODYNE and OPAC,
- Review of intersection control systems currently in operation at major cities.

I.3 Report organization

The second chapter contains the detailed analysis of the state-of-the-art intersection control software developed to date. The existing intersection control systems currently operating at major cities in the U.S. and Canada are reviewed in Chapter 3. Chapter 4 summarizes the current status of the video detection system developed in Minnesota. Finally, Chapter 5 includes conclusions and further research needs.

II. ADVANCED CONTROL STRATEGIES FOR SIGNALIZED TRAFFIC NETWORKS

II.1 Introduction

The most advanced concept for urban network management includes real-time, demand-responsive control strategies with on-line signal timing generators and adaptive control features. This type of control software is represented by SCOOT, SCATS, PRODYNE and OPAC, which are reviewed and compared in this chapter. With the lack of field evaluations directly comparing each software, this review focused on the analysis of the theoretical principles and implementation issues of each software found from the literature. The following sections summarize the advantages and limitations of each software including control algorithm structure, data collection methods.

II.2 Overview of the state-of-the-art intersection control software

II.2.1 Theoretical principles

The principles upon which the four algorithms depend vary from cyclical vs. acyclical and centralized vs. decentralized. In particular, SCOOT and SCATS seek to adjust the cycle time, phase split, and offset so that the optimisation criteria (i.e., stops, delays, and queue lengths) are minimised. By contrast, PRODYNE and OPAC attempt to find optimal acyclic settings.

SCOOT is based on centralised methods (it does not include microprocessor vehicle-actuated control tactics at local intersections), whereas SCATS performs much of the optimisation procedure (e.g., phase optimisation) in its vehicle-actuated controllers.

PRODYNE and OPAC, following a decentralised philosophy, perform the optimisation at each intersection through dynamic programming techniques and a rolling horizon. More specifically, OPAC minimises vehicle delays and percentage of stopped vehicles and PRODYNE attempts an explicit minimisation of total delay.

The differences between SCOOT and SCATS regarding the adjustment of the three fundamental control elements (i.e., cycle time, phase split, and offset) are outlined below.

Cycle Time

Both SCATS and SCOOT vary the cycle time according to the level of congestion. The two methods are, however, different in the following aspects:

(a) The frequency of cycle time change in SCOOT is restricted to, at most, once every 2.5 minutes, whereas SCATS can vary cycle time on a cycle by cycle basis.

(b) SCOOT has a double-cycling facility, i.e., an intersection can operate at half the network cycle time when network cycle time is high, and can return to single cycle when intersection demand decreases. SCATS can double or triple the cycle of minor intersections and it responds faster than SCOOT to demand variations.

Therefore, the two methods appear to be comparable in choosing a cycle time that is appropriate for the prevailing traffic conditions.

Phase Split

SCATS uses four predetermined phase split plans. These plans stipulate four different vehicle-actuated tactics, one for each of four flow patterns, usually distinguished by the time-of-day. Selecting the appropriate vehicle-actuated tactic is facilitated by the queuing data transmitted by the detectors in real time; as a result, a phase can be skipped if no vehicles are waiting. Therefore, SCATS responds to fluctuating traffic demand at an intersection without the usual delay of one cycle time.

Following a different modelling philosophy, SCOOT relies on the modelling of the queue length and the on-line estimation of the degree of saturation to optimise phase splits in small steps of a few seconds. Phase changes may not be frequent enough to meet the cycle by cycle variation of traffic demand. In addition, an urban traffic control system using SCOOT would not be able to use the facilities available from a microprocessor controller to optimise the phase split. This is in contrast with SCATS, in which phase split optimisation is largely performed in its vehicle actuated controllers. In summary, the SCATS algorithm and hardware configuration appear to be more capable of optimising phase splits to reduce delays and stops than the respective algorithms and hardware configuration of SCOOT.

Offset

An offset is closely related to the cycle time and phase splits, and all three control elements should ideally be optimised simultaneously. In SCATS, the offset plans are predetermined and selected to match the current cycle time, phase plans, or directional splits of traffic flow. Special care is required for preparing offset plans for grid-type networks. The offset can also be modified, as an option, according to the level of congestion. The objective of the SCATS offset selection algorithm can be broadly treated as the maximisation of the bandwidth for platoon progression. With detectors located at stoplines, it is difficult to monitor platoon progression, and no feedback information regarding the performance of the offset adopted currently exists. The offsets in SCATS appear to be more 'rigid' than in SCOOT : SCATS offsets are not generally set up to be continuously variable over the whole range of possible offsets. Changes in offset cannot be smoothed with ease, in agreement with the SCATS philosophy on bringing a new offset into operation as quickly as possible rather than allowing many cycles with intermediate offsets.

The SCOOT optimiser has the benefit of using a traffic model to simultaneously optimise all control elements, including offsets. Determining the sum of queue lengths that minimise total stops and delays along selected approaches is the optimisation objective. The cyclic flow profiles are used to predict the effect of offset changes on queue lengths. Since the SCOOT loop detectors are located near the upstream intersection, they can indicate whether a queue spills back to block that intersection. Such information can be used to initiate special action to prevent the blocking. In this case, the optimiser can use a 'congestion' offset different from that minimising delays and stops on the link. This offset is set to maximise the capacity and avoid blocking the link when the upstream intersection is green to the critical approach. Since the SCOOT offset optimisation philosophy can consider the queue progression, it appears to be better defined than the SCATS offset selection method.

II.2.2 Implementation Issues

In each intersection control algorithm, the control method and system are related and the methodology is heavily dependent on the system that implements it. Conclusions derived from the comparison of SCOOT, SCATS, PROLYN, and OPAC regarding implementation issues

are presented below.

Controllers

Regarding the local controllers, certain compatibility issues would have to be resolved before SCOOT and SCATS could be implemented in the U.S. since neither system is compatible with U.S. standard controllers. Further, the controllers used with SCATS (Philips and AWA) are expensive and could not be replaced within a SCATS installation, since they are an integral part of the SCATS design. To be sure, SCATS could operate using an interface to other types of controllers. However, such an interface would have to be designed and manufactured for this purpose and would probably cost more than the replacement of the controller or, at least, of the controller logic module. In addition, use of an interface would not provide all the functions that a SCATS controller provides.

Certain compatibility issues would also have to be resolved before OPAC could be implemented in the U.S. For instance, implementation of OPAC within a standard 170 controller (commercially available, microprocessor based controller capable of implementing a traffic control strategy, as given in the microcode within its EPROM) or its successor, the type 179 controller, is not possible without several modifications to the controller and to the OPAC algorithm. These modifications would include a new processor, such as an Intel 80286 or a Motorola 68020, at least 640 of processor RAM, at least 640 of EPROM or EEPROM, which could be overlaid onto the system RAM if necessary, and a system clock that will provide a processor cycle time of 0.1 microseconds or less. A math coprocessor would also be required, unless the processor speed or efficiency is increased to compensate for the lack of the coprocessor.

Detectors

Historically, loop detectors have been used for the implementation of all four methods. Loop based detectors can monitor the clearly defined zone of detection required to measure occupancy related conditions with accuracy and reliability that are sufficient for the operation of the methods. Nevertheless, for the approaches requiring only tactical detection with SCATS, almost any reliable form of detection can be used. For instance, in Australia, microwave

detectors are temporarily used on tactical approaches, where road maintenance delays the repair of loops [42]. Developments in detector technology, especially the infra-red and video types, appear promising and a video-based detection system is currently being tested with SCATS in Michigan.

SCOOT, SCATS, and OPAC require one detector for each link, whereas PRODYN uses two detectors per link. In SCOOT and OPAC, detectors are normally placed well upstream from the intersection, preferably just downstream from the previous one (SCOOT) or 120 to 180 m from the stopline (OPAC). Since the two systems measure the flow entering the link a considerable distance upstream from the intersection, platoon dispersion between entrance and exit detectors becomes a significant phenomenon.

For very long links in a SCOOT system, the detectors have to be positioned 80 to 100 m upstream from the stopline. In a SCOOT implementation, in locations where it is not possible to site a detector upstream of the stopline, the flow is measured by the detector downstream of the stopline. This 'filter' link facility is most commonly used in left turn lanes. 'Filter' links can use the same detector as used for the downstream link. 'Filter' links are treated in the same way as ordinary links and have their own cyclic flow profile stored. OPAC detectors are farther upstream than current U.S. practice, and in SCOOT detectors are placed closer to the upstream intersection than in most U.S. systems. Therefore, in order for SCOOT and OPAC to be installed in the U.S., the detectors would have to be replaced. Further, in OPAC additional detectors (call-only detectors for tactical detection) are placed at the confluences of driveways with the links.

SCATS requires the detectors placed at the stoplines. Therefore, it is difficult to monitor platoon progression and no feedback information regarding the performance of the adopted offset exists. Additionally, detecting whether a queue fills up the space between two intersections is not possible. Therefore, the operator is not able to take special action to prevent the blocking of the upstream intersection. In PRODYN, two detectors are required: One at the entrance of the link (or at about 200 m upstream, if the upstream intersection is farther), and the other at 50 m from the stopline to increase system reliability.

SCOOT is relatively insensitive to sensor failures, mainly because of the incremental nature of the optimiser: The algorithm uses small, frequent alterations of signal timings. By

the accumulation of a large number of these small changes, the optimiser evolves new timings. Therefore, a few poor decisions by the optimiser are of no great importance. Default procedures ensure that the performance degrades gradually to a fixed time plan if successive failures occur and are not rectified. Simulation studies suggest that benefits from SCOOT are lost if 15% or more of sensors are faulty. Experience to date indicates that, with appropriate maintenance procedures, fault rates of well below 5% could be attained. Nevertheless, urban areas in the U.S. and Europe often report 50% facility detectors in their network.

SCATS uses loops that are approximately 4.5 m long - the 'loop' is usually made by two smaller loops connected together. Since loops are very long, damages to the loop conductors are caused as a result of differential movements. If the operation of the loops is monitored at the regional computer level, loop faults can be detected by the regional computers. Typically, all the advantages of traffic responsive control can be achieved by the provision of detectors in representative lanes of each movement requiring accurate phase split adjustment at each critical or major intersection, and (optionally) detectors at adjacent intersections in representative lanes of approaches upstream of the primary strategic detectors at the critical intersections. In a typical system, 50 to 70% of approaches require detection in some lanes for maximum traffic responsiveness, but this can vary according to system complexity.

The SCATS advantage of detector redundancy, reducing the urgency with which critical faulty detectors have to be repaired, must be weighed against the disadvantage of greater maintenance costs of a larger number of detectors. For authorities not equipped for the repair of detectors, the system can be installed initially with fixed time operation and subsequently it can be gradually upgraded by the addition of detection at the most needy locations. The alterations to the system configuration are simply and easily effected with the system remaining on-line.

Processors

The computer system on which the four methods can be implemented vary. In particular, SCATS can only be implemented on a Digital PDP11. All SCATS software has been developed in an assembly language specific to Digital. It must be noted that most U.S. jurisdictions are equipped with either a microcomputer or minicomputer system. Thus, the

intersections may be sufficiently low to permit 'double cycling', i.e., operation on a cycle time which is one-half of the sub-area cycle time. In an extreme case, all but the critical intersection in a sub-area can be double cycled. However, since alterations between single and double cycle operation cause discontinuities in the signal timings and hence may disrupt the traffic flows, the SCOOT cycle time optimiser is designed to prevent unduly frequent alterations. The traffic engineer can also restrict specified intersections to either single or double cycled operation.

Public Transportation

A feasibility study conducted by the University of Southampton, UK, has looked at the feasibility and possible methods of incorporating bus priority within SCOOT. Bus priority methods proposed included 'passive' and 'active' techniques. 'Passive' (off-line) methods use biasing/weighing factors to adjust the green splits and/or the offsets to benefit traffic streams containing buses. 'Active' techniques individually identify buses in the mixed traffic stream and give them individual priority.

One of the 'active' methods analysed was the fully bus-responsive system, which provides priority green time extensions for buses, and compensation facilities for non-priority traffic in subsequent cycles. Additional 'active' systems analysed included methods such as 'on-line system using "shared stopline" modelling principles' and 'using "spare green" in each cycle to identify the time windows in which buses could be given priority'. The latter two methods showed most promise in that worthwhile bus priority could be obtained and could pay for itself within 12 to 24 months, without noticeably disbenefitting other traffic. Recommendations were made for further analyses to identify the conditions in which a 'passive' system would be more cost-effective than an 'active' one, and for simulation studies to determine the most appropriate form of 'active' system.

SCATS can specially treat trams. Such a tram priority facility has been implemented and evaluated in Melbourne, Australia.

Bicycles

Both SCOOT and SCATS can cater for the control of heavy bicycle movements. Bicycle detection is used in the SCOOT implementation in Beijing, China, and in the SCATS

implementation in Shenyang, China.

Minor Movement Tactical Detection

SCATS superimposes tactical vehicle and/or pedestrian detection to allow skipping or gapping of minor vehicle movements or pedestrian walk phases.

In OPAC, call-only detectors for tactical detection are placed at the confluences of driveways with the links. It is important that call-only detectors be present, since the OPAC detectors are located far upstream. Without call-only detectors, vehicles entering the traffic stream from driveways and shopping centers downstream of the OPAC detectors would not be detected. Without call-only detectors, even if there are not any vehicles waiting at the confluence of the driveway with the link, the system will assume there are vehicles waiting to enter the link and service them unnecessarily.

Finally, PRODYN developers plan to provide the algorithm with procedures coping with pedestrian crossings. In this case, the optimisation criterion is the sum of vehicle and weighted pedestrian delays. The algorithm developers have introduced methods for forecasting non-controlled inputs (i.e., pedestrian arrivals), such that an accurate estimation of the sum of delays be available.

Network Alterations

SCOOT can cope with short term unexpected detector failures and major works causing the removal of whole links and nodes from the network for a considerable period. The algorithm can adjust the timings on the remaining traffic signals by adjusting its database to remove the missing detectors. Such adjustment is performed on-line. This kind of continuous assessment and change can be an indication for the success of a city-wide system.

Traffic Information Availability

In the process of optimisation, the traffic model incorporated in SCOOT provides a wealth of traffic information, such as traffic flow/demand, delay, number of stops, queue length, congestion, degree of saturation, spare capacity, traffic signal settings, and system (e.g., detector) faults. This information is potentially useful for a variety of traffic research purposes.

the high installation and maintenance costs associated with loop detectors. Other detection technologies, such as the self-powered vehicle detector, might also offer the potential for eliminating the high lead-in costs.

II.2.4 Effectiveness-Accuracy-Benefits

In the absence of a field evaluation directly comparing SCOOT, SCATS, PRODYN, and OPAC, it is only possible to consider comparisons of each algorithm against older tactics, such as fixed-time or fully vehicle-actuated strategies. Generally, field tests have shown that all four methods improved the traffic situation in terms of delay, number of stops, and travel time. However, the benefits earned from each implementation are strongly related to the quality and age of the older strategy against which the comparisons were made. Therefore, the benefits from these tests are not comparable.

The effectiveness of the algorithms in terms of minimising network stops and delays depends on the accuracy with which the degree of saturation for each link is measured or estimated. The usual method of off-line estimating saturation flow for a link is based on off-line measuring link geometric characteristics, such as number of lanes, width of lanes, grade, etc. Such an approach cannot take into account variations of saturation flow that are due to special conditions. For instance, if a vehicle is parked on the stopline, one of the lanes is not available for saturation discharge of traffic. Similarly, if rain makes the road slippery, the rate of saturation discharge of traffic is reduced, i.e., actual saturation flow decreases compared to the off-line estimate.

By contrast, on-line methods measuring or estimating saturation flow can take into account such special conditions, since they count the number of vehicles passing over the detector during the saturation period and divide it by the duration of the saturation period. Generally, on-line methods have the advantage of self-calibrating saturation flows according to changes in intersection geometry, lane utilisation, weather conditions, and driver behavior.

Both SCOOT and SCATS use on-line saturation flow data as input to their control algorithms. Since the traffic input for the control is more accurate than off-line saturation flow estimates, the control output is expected to be also more accurate, thus more effective in terms of servicing the traffic with minimised stops and delays. However, SCOOT's SOFT facility,

estimating saturation occupancy on-line can only be applied in links with suitably placed downstream detectors. In SCATS, the level of congestion is indicated by the degree of saturation measured at the stoplines of preselected approaches in a network. PRODYN and OPAC do not provide the traffic engineer with facilities estimating on-line saturation flow rates. Methods for estimating on-line saturation flow rate have been proposed for PRODYN, but cannot cope with detector failures.

Turning movement ratios are additional parameters significant to the accuracy and effectiveness of the algorithms. PRODYN does not provide the traffic engineer with facilities estimating on-line turning movement ratios. The methods of on-line turning movement ratio estimation, proposed for PRODYN, cannot cope with detector failures.

In SCATS, counts of turning movements are particularly incomplete at approaches with 'right turn at all times', since no detectors are installed in those lanes to count right-turning vehicles. Nevertheless, techniques for estimating turning flows at a SCATS-controlled intersection are available. One of these techniques uses time series of vehicle counts. This method is based upon recursive least squares and is particularly suitable for on-line applications. An alternative method is based on the 'information minimisation' principle.

OPAC models left turning volumes, since the detectors are located well upstream (120 - 180 m) from the intersection. To accomplish this, the algorithm maintains a smoothed, expected duration for each minor phase. Based on the current expected phase durations and user-input discharge rates, estimated volumes for each minor phase are calculated. The calculated volumes are assigned to the minor phases and the total volumes, adjusted for the vehicles expected to turn left, are assigned to the major phases.

II.2.5 Applications

SCOOT and SCATS have been implemented in the urban traffic control systems of many cities worldwide and have demonstrated their ability to coordinate large arterial and grid networks. By contrast, PRODYN and OPAC have been implemented only for evaluation purposes on small networks. More specifically, SCOOT has been adopted mainly in the UK, but also in Canada, Spain, Saudi Arabia, and China. SCATS has been implemented mainly in Australia and New Zealand, but also in Ireland and China. It is also able to cope with large

arterial and grid networks.

PRODYN has not yet been applied in the field; however, it has reached the point where industrial development is possible. A first industrial development is taking place by a European consortium within the DRIVE program. It must be mentioned that all experiments to date have been conducted on isolated intersections or on small networks. Potential city-wide implementation has not yet been tested. Moreover, the topology of the network (arterial or grid) is significant - it influences the optimisation method used by the algorithm (hierarchical or decentralised).

Finally, OPAC also has not yet been applied in the field. To date the method cannot coordinate sets of intersections and can only be used for controlling an isolated intersection. While research on OPAC to date has concentrated on isolated intersection control, research has been performed in implementing the method in a network context. The results of field tests on isolated intersections have shown the positive response of the OPAC-RT system to platooned traffic, which is typical of arterial and network systems. Since the results exhibited by the isolated intersection version were positive, arterial or network optimisation with OPAC can be expected to reduce the delay to drivers.

II.3 Principles and facilities of each control software

II.3.1 SCOOT

SCOOT (**S**plit, **C**ycle, and **O**ffset **O**ptimisation **T**echnique) is a vehicle responsive traffic control signal system, developed by the British Government's Transport and Road Research Laboratory (TRRL). Subjects pertaining to the principles and the facilities provided by the algorithm, as well as conclusions related to the application, effectiveness, and accuracy of it, are described below.

Principles

The three key principles of SCOOT are:

1. Measure cyclic flow profiles in real time
2. Update an on-line model of queues continuously
3. Incrementally optimise signal settings

The sample time (time step) is 4 seconds [1,4].

Equipment-Hardware-Software

The equipment required for the implementation of SCOOT consists of vehicle detectors connected to the controlling computers via appropriate transmission lines.

One detector is required for each link. Although inductive loops have been used to date, other types of detectors can be used, providing similar information on vehicle presence [4,12]. The detectors are normally placed well upstream from the intersection, preferably just downstream from the previous one [4,12]. For very long links, which may contain more than one platoon at a time, the detectors must be placed 80-100 m before the stopline. In Beijing, bicycle sensors are placed 50-80 m before the stopline [3].

In the implementation of SCOOT in Beijing, China, the slot backfill used was epoxy resin. Plastic protective corner pieces were used, whereas in UK the acute or square corners of loop slots are often cut across at 45 degrees to reduce the strain of the cable against a sharp edge [3].

SCOOT is relatively insensitive to sensor failures, mainly because of the incremental nature of the optimiser: The algorithm uses small, frequent alterations of signal timings. By the accumulation of a large number of these small changes, the optimiser evolves new timings. Therefore, a few poor decisions by the optimiser are of no great importance. Default procedures ensure that the performance degrades gradually to a fixed time plan if successive failures occur and are not rectified. Simulation studies suggest that benefits from SCOOT are lost if 15% or more of sensors are faulty. Experience to date indicates that, with appropriate maintenance procedures, fault rates of well below 5% could be attained [3,4]. Nevertheless, it is accepted that in urban areas, 30 to 50 percent of detectors do not operate accurately at any given time.

SCOOT software is written in a high-level language and implemented on a variety of computer systems [24]. For example, in Wirral System a DECPDP11/83 computer is sufficient for 60 nodes treatment. In Aberdeen a VAX based system is used. In Madrid a DEC VAX computer is employed. If the traffic information provided by SCOOT is directed to a database, an IBM compatible PC is additionally required. In this case, use of dBASE and dGE graphics software packages is necessary.

Regarding the data transmission system, in the implementation of SCOOT in Beijing,

China, the communication system operates at a speed of 200 baud, leading to a transmission in each direction every second. The lines are provided by the normal telephone service. Occasional noise causes loss of 1 sec or 2 transmissions per hour on approximately 10% of the lines [3].

Facilities

SCOOT provides traffic engineers with a range of facilities that offer flexibility in implementing control strategies. These facilities are briefly described below.

A particular route can be favored by using a 'weighing' facility: The stops and delays of the route to be favored can be multiplied by large weighing factors in the objective function, such that large values of stops and delays on this route not be permitted at the optimal signal settings. This 'weighing' procedure - or the above mentioned 'gating' facility - are currently applied manually. However, expert systems may be used for this purpose in the longer term [1].

On-line saturation occupancy estimation method is available. The calibration time is reduced, when the system is first installed. Besides, SCOOT responds to variations in saturation flow, when, e.g., when vehicle is parked near the stopline [1,4].

Moreover, feedback of signal status into SCOOT for demand-dependent stages is available. Simulation studies have suggested that such feedback can lead to delay reduction of 5-10 % for a typical intersection, as a result of better distribution of the available green times. The higher reductions are obtained when the intersection is oversaturated and when the frequency of the demand dependent stage differs substantially from the one initially assumed [1].

Further, 'gating' and 'action at a distance' facilities are available. These facilities allow restriction of the inflow of traffic into a sensitive area upstream of a bottleneck to prevent the buildup of a long queue or congestion. Vehicles are redistributed to more acceptable roads. In addition, 'gating' can be set up so as to increase green to 'gated' links downstream of the bottleneck and clear the queues. This 'flow gating' procedure is currently applied manually. However, expert systems may be used for this purpose in the longer term [1].

Additionally, in a SCOOT system a link can use the congestion information from another

link: A link can be specified as 'supplier of congestion information' to another link. For instance, consider the network of Figure 2. Because link C is assumed a minor side road, the queue may be allowed to reach back to the detector on link A. Moreover, if the queue spills back to the detector on link B, the cause for this queue is likely to be the queue on link A. By specifying link B as a supplier of congestion information to link A, the traffic signals in intersection 1 will be affected by the blocking back occurring on link B [1].

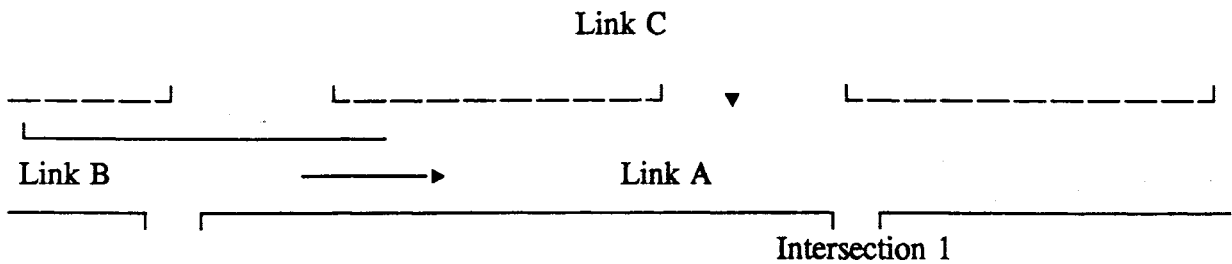


Fig. 1 Example of congestion facility

To cope with congestion, SCOOT employs congestion offsets that are different from those available for routine minimisation of stops and delays on a link. The congestion offset must be set to maximise capacity and avoid link blockage when the upstream intersection is green to the critical approach. These pre-specified congestion offsets are automatically implemented when queues cover the upstream detector [1,4].

In a SCOOT implementation, at locations where it is not possible to site a detector upstream of the stopline, the flow is measured by the detector downstream of the stopline. This 'filter' link facility is most commonly used in left turn lanes. 'Filter' links can use the same detector as used for the downstream link. 'Filter' links are treated in the same way as ordinary links and have their own cyclic flow profile stored [1].

SCOOT can cope with short term unexpected detector failures and major works causing the removal of whole links and nodes from the network for a considerable period. The algorithm can adjust the timings on the remaining traffic signals by adjusting its database to remove the missing detectors. Such adjustment is performed on-line. This kind of continuous assessment and change can be an indication for the success of a city-wide system [3].

SCOOT allows the traffic engineer to divide a town into one or more sub-areas and

group the signals within each sub-area. Cycle time may vary across sub-areas. However, the intersections within a sub-area operate on the critical intersection cycle time ('double cycle operation') or on the half of it ('single cycle operation'), according to traffic demand. Within each sub-area, SCOOT determines the cycle time for operating the most heavily loaded intersection at a degree of saturation of about 90%. Therefore, other intersections within the sub-area usually operate at below 90% saturation. The degree of saturation at certain intersections may be sufficiently low to permit 'double cycling', i.e., operation on a cycle time which is one-half of the sub-area cycle time. In an extreme case, all but the critical intersection in a sub-area can be double cycled. However, since alterations between single and double cycle operation cause discontinuities in the signal timings and may disrupt the traffic flows, the SCOOT cycle time optimiser is designed to prevent unduly frequent alterations. The traffic engineer can also restrict specified intersections to either single or double cycled operation [12].

SCOOT has a double-cycling facility, i.e., an intersection can operate at half the network cycle time when network cycle time is high, and can return to single cycle when intersection demand decreases [24].

In the process of optimisation, the traffic model incorporated in SCOOT provides a wealth of traffic information potentially useful for a variety of purposes. The Transportation Research Group (TRG) of Southampton University conducted a study related to the development a traffic database including such information. A questionnaire released by the researchers to a sample of transportation-related organisations presented a very high (over 90%) response rate. The responses evaluated the proposed database as valuable and ranked traffic flow as the most useful SCOOT datum. Approximately 50% of the responses proposed dBASE to be the software package to be used. Therefore, the ASTRID database was produced, providing information related to traffic flow/demand, delay, number of stops, queue length, congestion, degree of saturation, spare capacity, traffic signal settings, and system (e.g., detector) faults. Aggregations of the data are available on the detector, link, node, and region level, depending on the kind of information. Traffic flow trends, daily profiles, along with statistics and plots, are also available. Finally, the ASTRID database can cope with missing data caused by detector faults [2,5,7].

Bicycle logic has been incorporated in SCOOT. In the implementation of SCOOT in

Beijing, China, the algorithm operates in conditions of heavy bicycle flows. The optimiser is able to cope with bicycle links in the same way as with vehicle ones [1,3].

SCOOT provides traffic engineers with on-line messages indicating, e.g., degree of saturation, degree of congestion, occurrence of maximum queue and exit blocking, old and new standing queue, and queue clear time, [1]. The maximum queue validation is simplified by using the more readily measured on street parameter 'queue clear time for maximum queue' instead of the 'maximum queue value' [1]. Furthermore, SCOOT can model the queue buildup when SCOOT is overridden by an emergency plan (e.g., fire engine). Thus, the optimiser can dissipate the queue once it resumes control [4].

The 'fixed' offset logic is enhanced such that an offset can be fixed to an exact value and will only be moved from this temporarily by action of the cycle optimiser.

Start and end lags are provided by default and need to be provided only if they are different from those specified [1].

Potential Facilities (under research)

Procedures coping with various traffic problems, with respect to their potential incorporation into or collaboration with SCOOT, are currently under research. Some of these procedures are outlined below.

A part of the MONICA project within the EC's DRIVE pertains to the development of a method of traffic monitoring and incident detection, that uses information provided by SCOOT. The traffic monitoring takes place through the ASTRID database (TRRL, University of Southampton), which receives and processes data (flow figure, delay, and a congestion measure) and stores them at the level of link, node, region or route, depending on the kind of the data. The data processed are compared with corresponding 'limits', data lying within limits are accepted, whereas outlying data are considered indicative of abnormal traffic conditions, diverted to an 'outliers' file for separate analysis. Evaluation of the method commenced in Toulouse, France in March 1991 [4].

SCOOT is an important element of the TRRL work within DRIVE, since it can provide real-time data on congestion levels for input to an in-vehicle route guidance system, such as AUTOGUIDE. Moreover, if traffic is diverted by AUTOGUIDE to avoid an incident, SCOOT

can adapt the signal timings automatically to the new flow patterns. A DRIVE project is now investigating the dynamics of such interactions [4].

A feasibility study conducted by the University of Southampton, UK, has looked at the feasibility and possible methods of incorporating bus priority within SCOOT. Bus priority methods proposed included 'passive' and 'active' techniques. 'Passive' (off-line) methods use biasing/weighing factors to adjust the green splits and/or the offsets to benefit traffic streams containing buses. 'Active' techniques individually identify buses in the mixed traffic stream and give them individual priority.

One of the 'active' methods analysed was the fully bus-responsive system, which provides priority green time extensions for buses, and compensation facilities for non-priority traffic in subsequent cycles. Additional 'active' systems analysed included methods such as 'on-line system using "shared stopline" modelling principles' and 'using "spare green" in each cycle to identify the time windows in which buses could be given priority'. The latter two methods showed most promise in that worthwhile bus priority could be obtained and could pay for itself within 12 to 24 months, without noticeably disbenefitting other traffic. Recommendations were made for further analyses to identify the conditions in which a 'passive' system would be more cost-effective than an 'active' one, and for simulation studies to determine the most appropriate form of 'active' system [5].

Finally, a part of a project within the EC's DRIVE program performs analyses of journey time variability and prediction using SCOOT data [5].

Effectiveness-Accuracy-Benefits

The effectiveness of SCOOT in terms of minimising network stops and delays depends on the accuracy with which the degree of saturation for each link is measured or estimated.

The usual method of off-line estimating saturation flow for a link is based on off-line measuring link geometric characteristics, such as number of lanes, width of lanes, grade, etc. Such an approach cannot take into account variations of saturation flow that are due to special conditions. For instance, if a vehicle is parked on the stopline, one of the lanes is not available for saturation discharge of traffic. Similarly, if rain makes the road slippery, the rate of saturation discharge of traffic is reduced, i.e., actual saturation flow decreases compared to the

off-line estimate.

By contrast, on-line methods measuring or estimating saturation flow can take into account such special conditions, since they count the number of vehicles passing over the detector during the saturation period and divide it by the duration of the saturation period. Generally, on-line methods have the advantage of self-calibrating saturation flows according to changes in intersection geometry, lane utilisation, weather conditions, and driver behavior.

SCOOT uses on-line saturation flow data as input for its control algorithm. Since the traffic input for the control is more accurate than off-line saturation flow estimates, the control output is expected to also be more accurate, thus more effective in terms of serving the traffic with minimised stops and delays [1].

In addition, provided that key SCOOT parameters are correctly validated to reflect on-street conditions, SCOOT data are accurate for traffic management and associate purposes [2].

The effectiveness of SCOOT is being assessed by major trials in 5 cities in the UK. The results from these trials are summarised in Tables 2 [4], and Table 3 [12,24]. In most cases, comparisons are made against a good standard of fixed time coordination, usually based on TRANSYT. Table 2 shows that the largest benefits are gained in comparison with isolated vehicle actuation, but, of course, part of such benefits could be achieved by a good fixed time system. The relative effectiveness of SCOOT varies by area and time of day, but overall SCOOT achieves an average saving in delay of about 12 % compared with good fixed time plans. Since SCOOT does not 'age' in the way of typical fixed time plans, SCOOT should gain savings in many practical situations of 20 % or more, depending on the quality and age of the previous fixed time plan and on the rapidity with which flows change [4,12]. Table 3 indicates

TABLE 2 : Reduction in Delay from the Use of SCOOT in UK [4]

Location	Previous Control	Percent Reduction in Delay Time		
		AM Peak	Off Peak	PM Peak
Glascow	Fixed time	-2	14*	10*
Coventry	Fixed time			
Colehill Road		23	33*	22*
Spon End		8	0	4
Worcester	Fixed time	11	7*	20*
	Isolated VA	32*	15*	23*
Southampton	Isolated VA	39*	1	48*
London	Fixed time	(Average 8% less journey time)		
* : results significant at the 95% confidence level				

that SCOOT is better than fixed time tactics in the off-peak and PM peak periods. Based on these results, Hunt et al [24] suggested that SCOOT is more effective when traffic demand approaches intersections capacity when demand is unpredictable, and when the distances between intersections are short.

The Beijing survey results are summarised in Table 4. This Table shows a reduction in delay between 15 and 41 %, depending on the time period. The number of stops was reduced by 25 %. The best journey time improvements of 15.9 % are in the AM vehicle peak. However, it must be taken into account that the previous fixed time plan was quite aging. Besides, the floating car evaluation was rather invalid [3].

According to the Hong Kong Commissioner of Transport, the application of SCOOT on Hong Cong island brought about 30% savings in journey time. However, it must be taken into account that prior to SCOOT's application there was not even a fixed time plan operated in Hong Kong [11].

TABLE 3 : Reductions in Delay from the Use of SCOOT in UK [24]

City	Network Type	Evaluation Criterion	Percentage difference in Comparison with Fixed Time Control			
			AM Peak	Off Peak	PM Peak	Late PM
Coventry	Arterial	Network travel time per km [sec]	6	4*	8*	+
Glasgow	Grid		-1	7*	6*	+
* : results significant at the 95% confidence level						
+ : results not available						

Finally, Siemens Plessey Company completed validation of SCOOT Version 2.4 on a 23 node network and was granted British Department of Transport approvals in December 1990 to continue with the next stage [21].

The use of SCOOT seems to be more beneficial when the flow is heavy, complex, and varying [4]. For example, the feedback of signal status into SCOOT for demand dependent stages leads to delay reduction up to 5-10% for a single intersection compared to the operation of SCOOT without such feedback. The higher reductions are achieved when the intersection is oversaturated and when the frequency of the demand depended stage differs substantially from the initially assumed [1].

TABLE 4 : Savings from Use of SCOOT in Beijing, China [3]

Time of Day	Reduction		
	Stops [%]	Stopped Time [%]	Journey Time [%]
7:00 - 8:00	25.65	41.05	7.06
8:30 - 9:30	32.66	32.30	15.85
12:30 - 13:30	13.69	15.15	4.35
17:00 - 18:00	28.97	18.96	1.78

Additional advantages of SCOOT include software which is written in a high-level language and implemented on a variety of computer systems [24]. Thus, there is much flexibility regarding to its implementation in the field.

SCOOT does not allow sudden changes in signal timings. In particular, to ensure that the total traffic benefits exceed the initial disbenefits during the transition from one timing plan to another, SCOOT requires a new plan to operate over a number of minutes before it may be changed. This tactic may be beneficial, since a new plan must operate for at least ten to fifteen minutes to ensure that the total traffic benefits exceed the initial disbenefits during the transition from one timing plan to another [12].

Limitations

In SCOOT, detectors are normally placed well upstream from the intersection, preferably just downstream from the previous one (SCOOT). Since SCOOT measures the flow entering the link a considerable distance upstream from the intersection, platoon dispersion between entrance and exit detectors becomes a significant phenomenon [22].

To compact congestion, SCOOT uses a vertical queue evolution model. When congestion begins, at least one queue develops and grows (primary congestion) and, if congestion grows, an upstream intersection is blocked by a downstream queue (secondary congestion). This model works well under free flow ('fluid') conditions and for primary congestion, since in these cases the output flow is not affected by downstream queues. However, the model is disabled in the presence of secondary congestion, where the output flow is affected by downstream queues. In order to cope with secondary congestion, the set of solutions must never to be empty, independently of the demand, i.e., the system must always have a solution with which to operate, even when the optimisation problem has no feasible solutions, due to conflicting constraints. A strategy dealing with this problem and tested with PRODYN leads to the horizon augmentation concept and, to congestion prevention. Using this strategy, the unavoidable congestion is shared among links proportionally to their capacities. The method tested with PRODYN resulted in 37% travel time improvement compared to travel times of PRODYN without employing the proposed strategy. The above described concepts may apply to SCOOT [18].

Additional limitations to SCOOT are as follows:

- SCOOT's SOFT facility, estimating saturation occupancy on-line can only be applied in links with suitably placed downstream detectors [1].
- Because of detector location requirements, SCOOT cannot be implemented on a SCATS system, even though the SCOOT software is largely independent of the computer system [24].
- The frequency of cycle time change in SCOOT is restricted to, at most, once every 2.5 minutes [12,24].
- The queue length prediction cannot be completely accurate, because some vehicles that cross the SCOOT detector may park or turn off down a side road before reaching the stopline [12].
- SCOOT does not include microprocessor vehicle actuated control tactics at local intersections [24].

Finally, certain compatibility issues would have to be resolved before SCOOT could be implemented in the U.S.A. SCOOT is not compatible with U.S. standard controllers. In addition, in SCOOT, vehicle detectors are placed closer to the upstream intersection than in most current U.S. systems. Therefore, in order for SCOOT to be installed in the U.S., the detectors would have to be replaced [28].

Applications

SCOOT has been implemented in the urban traffic control systems of over 40 cities in the UK and overseas [1,2,4] and has demonstrated its ability to coordinate large arterial and grid networks. Cities that have implemented SCOOT include London, UK (250 signals; planned extension up to 1200); Glasgow, UK; Coventry, UK; Worcester, UK; Southampton, UK [4]; Liverpool, UK (Caryl St. area) [10]; Red Deer, Canada; Halifax, Canada; Hong King [11]; Aberdeen, UK (150 nodes) [8]; Madrid, Spain (131 nodes; planned extension up to several hundreds) [21]; Manama, Bahrein (20 nodes; planned extension) [9]; and Beijing, China [3].

II.3.2 PRODYNE

PRODYNE is an urban traffic control method, which has been developed over the last decade by Centre d' Etudes et des Recherches de Toulouse (C.E.R.T.), France. The algorithm computes, in real time, the best signal settings with respect to the delay criterion for varying demand in traffic networks. Topics related to the principles and the facilities provided by the strategy, as well as conclusions pertaining to its application, effectiveness, and accuracy of it, are described below.

Principles

PRODYNE attempts to find acyclic settings, unlike SCOOT, which is based upon cyclic settings [13]. The main characteristics of the method are explicit minimisation of total delay and use of automatic control, Bayesian estimation, dynamic programming, and decentralised methods [16]. More specifically, the optimisation procedure is performed, for each intersection, through an adapted forward dynamic programming algorithm looking for the control on a rolling horizon [15]. The algorithm utilises a 5 seconds sample time: The control is the decision to switch over from one stage to another [13,16,20].

Equipment-Hardware-Software

The equipment required for the implementation of PRODYNE consists of detectors providing the controlling computer with traffic information via appropriate transmission lines. Two magnetic loop sensors are used by lane: One at the entrance of the link (or at about 200 m upstream, if the upstream intersection is farther) and the other at 50 m upstream of the stopline [15,16,20].

PRODYNE has been implemented for evaluation under a prototype version on the ZELT system. The entire system consists of:

- (i) Acquisition module containing several boards, each board managing transmissions with a few intersection controllers on field.
- (ii) Various control modules also containing several boards, each board performing PRODYNE computations for a single intersection. The control boards used are INTEL 8086 with 8 MHz clock frequency.

(iii) Micro-VAX II.

(iv) INTEL 310 development station [16].

Each intersection is controlled by a microprocessor board. Processors controlling neighbor intersections communicate using the ZELT basic software through the ETHERNET network. (Whenever hierarchical control is used, microprocessors supervising several intersection microprocessors are required). The ZELT basic software supplies to each board, every 100 msec, a frame containing all detector information and makes possible remote control of the intersection controllers on the field.

The PRODYN software of each board is written in C language, occupying 50 Kbytes of memory and it includes two major tasks; the first task is low priority, activated every 5 sec, and realising the algorithmic computations. The second task is high priority task, being activated at every frame reception, performing computations of flows from raw detector data, and replying to orders coming from the ZELT experiment supervisor (start and stop of experiment etc.). Under that implementation, the low priority task uses an average cpu time of 2.3 sec, with a maximum of 4.3 sec [13,15,16,20].

The memory requirements for an intersection of 4 links are 10.53 Mbytes. This number is very high, and has been lowered to 2.216 Kbytes by considerations on state equation, segmentation, and dynamic allocation of memory [13]. During the optimisation, the memory needs not to be allocated to all existing subsets, but only to the ones effectively reached [16].

Potential Facilities (under research)

PRODYN has reached the point where industrial development is possible. A first industrial version is under development by a European consortium in the DRIVE program [20]. Further research has been made in order to improve the PRODYN algorithm. In particular, methods for on-line estimation of the PRODYN input parameters, such as Turning Movement Ratios (TMR) and Saturation Flow Rates (SFR), have been proposed. Variations in these two parameters strongly effect the control efficiency. For example, in a two intersection network, a TMR difference of 20% produces an 8% loss of optimality in total presence time. The total presence time degradation for a four arm intersection is higher, 16 to 21%, depending on the value of the saturation flow parameter. The proposed TMR estimation methods are based

either on least-square minimisation or on Kalman filtering. Whereas, SFR estimation strategies are based either on an identification of the flow-occupancy logarithmic relationship for a single sensor located at the traffic light stopline or on the use of various sensors or, finally, on concomitant estimation of queues and SFR. The penultimate method uses actual PRODYN sensors, whereas the last one is based on a new location for loops. It has been shown that the above methods are not only satisfactory, but also compatible with PRODYN. However, these methods cannot cope with detector failures [17,20].

The criterion optimised is the sum of vehicle delay and weighted pedestrian delay. Methods for forecasting non-controlled inputs (pedestrian and vehicle arrivals) and estimating state variables are developed. The rolling horizon optimisation of the pedestrian crossing is performed via a forward dynamic programming algorithm [8,9].

An upper coordination level controlling PRODYN under oversaturated conditions is defined where the short range delay criterion is not sufficient to ensure good network control [20].

Effectiveness-Accuracy-Benefits

A prototype version of PRODYN has been tested using the ZELT experimental area in Toulouse, France. An experiment was conducted in 1987 on an isolated intersection in order to evaluate the right functions of the prototype. A second experiment, conducted in 1988, allowed a comparison between PRODYN and optimised fixed time plans on a 7 intersection network.

More specifically, the isolated intersection experiment was conducted on a T junction with high flow in the main direction and lower flow in the secondary direction, except during morning peak. The results, are summarised in Table 5, indicates that, concerning the number of stops, PRODYN works better than classical adaptivity, but fixed time is better outside peak periods. This conclusion is not surprising, since the optimised criterion, total delay, is not necessarily directly related to stops [20].

TABLE 5: Gains in the Number of Stops from the Use of PRODYN on an Isolated Intersection [20]

Period	8:00-9:00	9:30-11:00	18:00-19:30
Critical Gap	858	1016	507
PRODYN	809	915	750
Fixed Time	839	867	699
Difference			
PRODYN/C.G.[%]	6	10	3
Significance			
Probability[%]	80	99	51
Difference			
PRODYN/F.T.[%]	4	-6	-12
Significance			
Probability[%]	58	91	98

TABLE 6: Gains in Total Presence Time [veh*hr/hr] from the Use of PRODYN on a 7 Intersection Network [20]

Period	8:00-9:00	15:00-16:15	16:45-18:00	Overall
PRODYN	66	58	76	66
Fixed Time	75	62	83	73
Difference				
PRODYN/F.T.	12	6	8	10
Significance				
Probability[%]	95	85	95	99.99

The comparison between critical gap and fixed time shows that the intersection was not quite suited for an adaptive control. Other experiments [23] have shown that the critical gap technique is more efficient than optimised fixed time. This is mainly due to the existence of a very long minimum green time on the secondary entrance, where traffic is very low except during the morning peak. Thus, the best results for adaptive control are observed during the morning peak period. Therefore, the results for PRODYN, which is always more efficient than conventional adaptivity or fixed time, are satisfactory enough to consider a full-scale experiment on a network [20].

Regarding travel times, a statistical analysis of the travel time histograms corresponding to each period of time was performed, in order to characterise the various algorithms by the

mean value of travel time, and by notions concerning the structures of travel times, as seen through the shapes of histograms. In critical gap methods, green is kept on an entrance as long as vehicles arrive close enough to each other. A high number of vehicles cross the intersection without being stopped, but waiting times can vary. In PRODYN, which makes a global optimisation, travel times are dispatched around the mean value. This analysis has made clear that, even in the cases when PRODYN results in longer travel time, the dispersion remains lower: Travel times with PRODYN are thus more regular [20].

The network experiment was conducted in a 7 intersection area, constituting the northern part of the ZELT area. This network presents two main axes, with heavy traffic and frequent congestion, even outside the peak periods, and secondary streets, where traffic is very light outside peak periods.

The results for total presence time, after elimination of the demand effects by linear regression, are presented in Table 6. PRODYN is more efficient than fixed time on every period with a high degree of significance. Globally speaking, a significant decrease of 10% in presence time is observed, which corresponds, considering a free flow speed of 60 km/h, to a decrease of 12% in delays.

The improvement observed in the isolated intersection experiment is due to two factors. The first is that the intersection chosen for the first experiment was not well suited for adaptive control. Even a good adaptivity method could not be much better than a fixed time plan. The second factor is that some improvements have been implemented into the PRODYN program, and some errors were corrected between the two experiments [16,20].

Regarding delay, results have shown substantial gains - to give an idea, of about 16% with respect to fixed time policies. In particular, PRODYN was tested on a 4 intersection network, for 3 different demand patterns. Gains in delay, presence time, and stop time were achieved using PRODYN instead of good TRANSYT plans. The size of these gains depend on the demand pattern [14].

Limitations

PRODYN does not provide the traffic engineer with facilities estimating on-line saturation flow rates (SFR) and turning movement ratios (TMR). Methods for estimating on-

line SFR and TMR have been proposed for PRODYN, but cannot cope with detector failures [17].

PRODYN has been shown slightly less efficient than fixed time plans regarding total presence time when perturbation occurs and, particularly, when congestion originates at the downstream intersections [20].

In PRODYN, the objective function to be minimised is the accumulated expected queue at the intersections of interest. To estimate the queue length, arrivals are considered binomially distributed. The queue length evolution forms a Markov chain, leading to objective function calculations that require manipulation of large probability arrays. Such manipulation is inefficient in terms of computer time and storage. Several approximate methods for the calculation of the objective function are in good agreement with the Markov approach [21].

PRODYN performance is worse than fixed time plans during the off-peak period in terms of number of stops. This is not surprising, since the algorithm minimises the total delay, which is not necessarily directly related to stops [20].

If PRODYN-H (hierarchical control, appropriate for arterials) is used, several problems arise, such as:

- The algorithm cannot coordinate more than 10 intersections.
- High capacity communication links are needed.
- If the microprocessor that supervises several intersections fails, all area controllers of these intersections fail.
- Complex computations are necessary.

However, PRODYN-02(e) (decentralised coordination, appropriate for grid networks), in which adjacent controllers exchange information, gives very good results for arterials, even compared to PRODYN-H [14].

All experiments to date have been conducted on isolated intersections or on small networks [16,20]. Potential city-wide implementation has not been tested yet.

Finally, if PRODYN is used, the network topology (arterial or grid) is significant; it influences the control method choice (hierarchical or decentralised) [14].

Applications

PRODYN has not yet been applied in the field. However, it has reached the point where industrial development is possible. A first industrial version is now under development by a European consortium in the DRIVE program [20].

II.3.3 SCATS

SCATS (Sydney Coordinated Adaptive Traffic System) is a vehicle actuated control method developed by the Department of Main Roads, New South Wales, Australia. Issues pertinent to the principles and the facilities provided by the method, as well as conclusions related to its application, effectiveness, and accuracy are described below.

Principles

SCATS divides an area into smaller sub-areas of about 1 to 10 intersections sharing a common cycle time. Each sub-area contains one critical intersection, for which the sub-area's green split plans, internal and external offset plans, and cycle lengths are selected. Green splits are altered every three cycles; offsets are altered every five cycles; cycle time is altered in steps of up to 6 seconds, according to the degree of saturation of the critical intersection of the sub-area, on a cycle by cycle basis. The degree of saturation is measured using detectors.

SCATS method first determines the cycle time required for each sub-area. This cycle time is shared among various phases at each intersection according to a selected phase split plan. The offset plan within a sub-area may be, by default, one selected by an algorithm which may also be used to select an external offset for sub-system "marriage", or, optionally, one which is tied to the phase split plans [24,25,28].

Equipment-Hardware-Software

The equipment required for the implementation of SCATS consists of detectors connected to the controlling computer via appropriate transmission lines.

The detectors are located at the stoplines [24]. Typically, all the advantages of traffic responsive control can be achieved by the provision of detectors in representative lanes of each

movement requiring accurate phase split adjustment at each critical or major intersection, and (optionally) detectors at adjacent intersections in representative lanes of approaches upstream of the primary strategic detectors at the critical intersections. In a typical system, 50 to 70% of approaches require detection in certain lanes for maximum traffic responsiveness, but this can vary according to system complexity. The advantage of detector redundancy, reducing the urgency with which critical faulty detectors have to be repaired, must be weighed against the disadvantage of greater maintenance costs of a larger number of detectors. For authorities not equipped for the repair of detectors, the system can be installed initially with fixed time operation and subsequently can be gradually upgraded by the addition of detection at the most needy locations. The alterations to the system configuration can be implemented with the system remaining on-line.

Loop based detectors can monitor the clearly defined zone of detection required to measure occupancy related conditions with accuracy and reliability that are sufficient for the operation of the methods. Nevertheless, for the approaches requiring only tactical detection with SCATS, almost any reliable form of detection can be used. For instance, in Australia microwave detectors are temporarily used on tactical approaches, where road maintenance delays the repair of loops [27]. Developments in detector technology, especially the infra-red and video types, appear promising and a video-based detection system is being tested with SCATS in Michigan.

SCATS can only be implemented on a Digital PDP11 computer. All SCATS software has been developed in assembly language specific to Digital [24]. The computer system operates as follows. For each intersection a microprocessor pre-processes data before forwarding them to the SCATS computer for strategic decision-making. The pre-processing enables large amounts of information to be passed to the regional computer, while maintaining reasonable communication overheads. The availability of a microprocessor has enhanced the form of local intersection control. Complex phasing arrangements for all priority movements are achievable using the intelligence of the microprocessor [25]. A single regional computer can economically control signals at up to 120 intersections. The system is expandable by simply installing additional regional computers, but a central monitoring computer is usually added, which allows centralised access to the regional computers for data input, monitoring,

and traffic data collection. When a SCATS installation exceeds 300 to 400 signals, the VAX Central Management Computer option should be added to the system in order to maintain and manage the system effectively (data collection and analysis, data backup, fault analysis, system inventory facilities easing the logistic burden of managing systems of that size). Generally the minimum requirement is a Micro-VAX II with VAX-VMS operating system and RDB database, at least 6 Mbytes of memory, 200 Mbytes of disk storage, cartridge tape drive, color plotter, line printer, printers, and VDU's as required [27].

Operator interface to SCATS may be by keyboard printer terminal (e.g., DEC LA120), visual display unit (e.g., DEC VT220), or by a PC acting as a workstation terminal. Suitable PC's are IBM-AT compatible with high resolution color screen, color graphics (EGA or VGA 640*480), with a minimum of 1 Mbyte RAM, a fixed disk of at least 30 Mbytes capacity, and a floppy disk drive of at least 360 Kbytes capacity [27].

SCATS is compatible with both AWA and Philips controllers manufactured in Australia [27]. The local controllers are connected in a star network by standard voice grade telephone lines or a dedicated cable network. One cable is required between the regional computer and each local controller. Messages are sent to each local controller every second. Data are transmitted at 300 bps full duplex, asynchronous, frequency shift keying (FSK). The regional computers are connected in a star network by either leased high speed data lines or a dedicated cable network. One line is required between the CMS computer and each regional computer. Data are transmitted at 4800 bps full duplex, synchronous, FSK, using any suitable data modem [25,27].

Facilities

SCATS provides traffic engineers with a range of facilities, that can aid in variation of cycle time once every cycle [24]. In addition, the level of congestion in SCATS is indicated by the degree of saturation measured at the stoplines of the preselected approaches in a network. SCATS has the advantage of self-calibrating saturation flows according to changes in intersection geometry, lane utilisation, weather conditions, or driver behavior [24].

Any sub-system or group of sub-systems may be defined to operate under fixed time/time-of-day plan selection. The plans available are numerous: For each intersection 8

split plans and 8 offsets are available. For each of their 64 possible combinations, cycle time can be specified in 1 second increments from 20 to 190 seconds. Tactical vehicle and/or pedestrian detection may be superimposed if required to allow skipping or gapping of minor vehicle movements or pedestrian walk phases. A combination of both fixed time and traffic responsive operation can be specified within one regional computer. A part of a SCATS system can operate under fixed time/time-of-day plan selection, and apply traffic responsive strategic and tactical operation to only the most critical intersection or sub-systems in the system. In effect, any sub-system may be defined to operate in a broad spectrum of modes, ranging from fully fixed time/time-of-day to fully traffic responsive. SCATS is also able to double or triple cycle minor intersections [27].

Scat includes techniques which estimate turning flows at a SCATS-controlled intersection. This is accomplished using time series of vehicle counts. This method is based upon recursive least squares and is particularly suitable for on-line applications. An alternative method is based on the 'information minimisation' principle [30].

Additional facilities are as follows:

- The critical intersection in a sub-area does not have to be critical at all times. For example, in one sub-area, one intersection may be critical during AM peak and another during PM peak. The two intersections may be specified in the same sub-area or may be placed in separate sub-systems, permanently linked together [27].
- The operation of the loops is monitored at the regional computer level; i.e., loop faults are detected by the regional computers [27].
- SCATS can adequately control heavy bicycle movements. Bicycle detection is used in the SCATS installation in Shenyang, China [27].
- Tram priority facility is available, implemented and evaluated in Melbourne, Australia [25].

Effectiveness-Accuracy-Benefits

The effectiveness of SCATS in terms of minimising network stops and delays depends on the accuracy with which the degree of saturation for each link is measured or estimated. The usual method of off-line estimating saturation flow for a link is based on off-line measuring link geometric characteristics, such as number of lanes, width of lanes, grade, etc. Such an

approach cannot take into account variations of saturation flow that are due to special conditions. For instance, if a vehicle is parked on the stopline, one of the lanes is not available for saturation discharge of traffic. Similarly, if rain makes the road slippery, the rate of saturation discharge of traffic is reduced, i.e., actual saturation flow decreases compared to the off-line estimate.

By contrast, on-line methods measuring or estimating saturation flow can take into account such special conditions, since they count the number of vehicles passing over the detector during the saturation period and divide it by the duration of the saturation period. Generally, on-line methods have the advantage of self-calibrating saturation flows according to changes in intersection geometry, lane utilisation, weather conditions, and driver behavior.

SCATS uses on-line saturation flow data as input for its control algorithm. Since the traffic input for the control is more accurate than an off-line saturation flow estimate, the control output is also expected to be more accurate, thus more effective in terms of servicing the traffic with minimised stops and delays.

SCATS results from Sydney, Australia are summarised in Tables 7 and 8. This evaluation adopted the floating car technique. The performance of SCATS did not differ greatly from that of TRANSYT in the CBD network and this confirmed that the network was highly constrained. On the other hand, the less constrained arterial GWH showed marked performance improvements as a result of SCATS coordination. SCATS consistently performed better than TRANSYT, although the 4% difference in journey time was not significant at the 95% level. SCATS reduced stops by 25% compared with TRANSYT. The overall result, including both the CBD and the GWH over the whole survey period, indicates that SCATS was of similar performance to TRANSYT in journey time, but was 9% better in stops [24].

Additional advantages of SCATS include smooth cycle time and split variations. In particular, cycle time varies by only a few seconds per cycle, except for light traffic conditions, where larger changes can be tolerated. The same is true for split variations, which, at critical intersections, are limited to a few percent of cycle time each cycle. At other intersections, larger changes in split can occur, but they are more acceptable at these non-critical sites [27].

A particularly user-friendly aspect of SCATS is that no depth of computer expertise is needed to carry out all traffic-related applications. Direct access to the operating system is not

required by normal operators. Redimensioning to add intersections or sub-systems to the network is carried out on-line without interruption to the traffic function. Even a new version of SCATS software can be easily installed without knowledge of the operating system or any depth of computer knowledge [27].

TABLE 7: Comparison of SCATS and TRANSYT in Sydney, Australia [24]

Area	Journey Time % Difference				Stops % Difference			
	Total	Lunch	PM	Late PM	Total	Lunch	PM	Late PM
CBD area Paramatta	-3	-6*	0	-1	1	-2	2	9*
GWH arterial Paramatta	4	0	2	9	25*	27*	21*	26*
Total	0	-4	2	3	9*	8*	10*	14*

* : results significant at the 95% confidence level
Lunch : 12:00 - 14:30
PM : 15:00 - 18:00
Late PM : 18:30 - 20:00
Total : 12:00 - 20:00

TABLE 8: Evaluation of SCATS in Sydney, Australia [24]

City	Network Type	Evaluation Criterion	% Difference Compared to Fixed Time Control			
			AM Peak	Off Peak	PM Peak	Late PM
Sydney						
- Newtown	Arterial	Network Travel Time [veh*hr/hr]	39*	8	35*	35*
-Paramatta	Arterial and grid		+	-4	2	3

* : results significant at the 95% confidence level
+ : results not available

After SCATS is initially set up under a contract in a city, several options for expansion of the system and enhancement of the software are available. For instance, expansion of the system may be carried out by contract as with the initial installation (viz Singapore), or by purchasing the required hardware only and implementing it with internal resources (viz Shanghai). Sufficient training for this purpose can be made available either under the initial contract or as a separate exercise.

Enhancement of the software falls into two categories. In the case of the traffic control software (i.e., that in the local controller regional computer) it is generally not possible for the user to make modifications, as this would render the system insupportable. Enhancement of these packages is undertaken by the Roads and Traffic Authority (RTA) on behalf of the user and made available to all users by way of software upgrade in much the same way as operating systems and PC packages are maintained. In the case of the VAX and PC terminal environment, the user can develop software to meet individual requirements. For example, in Shenyang, China, the user developed its own PC graphics software and wall map driving software [27].

Limitations

SCATS presents certain limitations regarding the hardware system, loop detectors adjustment of offsets and compatibility of controllers. Details of each limitation is briefly discussed below.

The SCATS algorithm and the SCATS hardware system are inseparable. The SCATS control method can only be implemented on a Digital PDP11 computer. All SCATS software has been developed in assembly language specific to Digital. It is possible to rewrite SCATS software to run on microcomputers or minicomputers, but this tactic does not seem to be cost-effective [24,27].

SCATS uses loops that are approximately 4.5 m long - the 'loop' is usually made by two smaller loops connected together. Since loops are very long, damages to the loop conductors are caused as a result of differential movements [27].

With detectors located at stoplines, it is difficult to monitor platoon progression and there is no feedback information regarding the performance of the offset adopted.

Additionally, there is no ability of indicating if a queue fills up the space between two intersections. It is not therefore possible to take special action to prevent the blocking of the upstream intersection [24].

The offsets in SCATS appear to be more rigid than in other systems: SCATS offsets are not generally set up to be continuously variable over the whole range of possible offsets. Changes in offset cannot be smoothed with ease in agreement with the SCATS philosophy on bringing a new offset into operation as quickly as possible rather than allowing many cycles with intermediate offsets [27].

SCATS counts of turning movements are incomplete at approaches with 'left turn at all times' or 'slip' lanes, because no detectors are installed in those lanes. Thus, there are techniques estimating turning flows at a SCATS-controlled intersection. One of these methods utilises time series of vehicle counts. This method is based upon recursive least squares and is particularly suitable for on-line applications. An alternative method is based on the 'information minimisation' principle [30].

Finally, certain compatibility issues would have to be resolved before SCATS could be implemented in the U.S.: namely, SCATS is not compatible with U.S. standard controllers. Further, the controllers used with SCATS (Philips and AWA) are expensive and could not be replaced within a SCATS installation, since they are an integral part of the SCATS design. To be sure, SCATS could operate using an interface to other types of controllers. However, such an interface would have to be designed and manufactured for this purpose and would probably cost more than the replacement of the controller or, at least, of the controller logic module. In addition, use of an interface would not provide all the functions that a SCATS controller provides [27, 28].

Applications

SCATS has been implemented in the urban traffic control systems of several cities worldwide, as shown in Table 9 [27]. The algorithm has demonstrated its ability to coordinate large arterial and grid networks.

TABLE 9: List of SCATS systems, July 1991 [27]

City	No of Inter-sections	No of Regional Computers	Central Monitoring Computers	Central Management Computers	Closed Circuit TV
AUSTRALIA					
Sydney *	1529	20	1	1	yes
Newcastle	93	1	0	0	no
Wollongong	61	1	0	0	no
Cosford	14	1	0	0	no
Haitland	11	1	0	0	no
Hobart	47	1	0	0	yes
Burnie	11	1	0	0	yes
Launceston	16	1	0	0	no
Melbourne *	1611	18	1	2	yes
Adelaide *	425	8	1	1	no
Perth	177	3	1	0	no
Canberra	134	2	1	1	no
Adelaide City	70	1	0	0	no
Darwin	22	1	0	0	no
NEW ZEALAND					
Auckland	128	2	0	0	yes
Hanukau	68	1	0	0	no
North Shore	36	1	0	0	no
Waitakere	8	1	0	0	no
Dunedin	48	1	0	0	no
Wellington	75	1	0	0	no
Christchurch	52	1	0	0	yes
Whangarhei	9	1	0	0	no
Hamilton	25	1	0	0	no
New Plymouth	13	1	0	0	no
CHINA					
Shanghai *	150	2	1	1	yes
Shenyang	50	1	0	0	yes
SINGAPORE					
Singapore *	315	3	1	1	no
IRELAND					
Dublin *	43	1	1	1	yes
* : computer graphics available					

II.3.4 OPAC

OPAC (Optimised Policies for Adaptive Control) is a vehicle responsive traffic control signal system, recently developed in the United States. Subjects pertaining to the principles and the facilities provided by the algorithm, as well as conclusions related to the application, effectiveness, and accuracy are described below.

Principles

OPAC features a dynamic optimisation algorithm which provides the computation of signal timing without requiring a fixed cycle time. The signal timing is constrained only by minimum and maximum green times. The optimisation criteria to be minimised are vehicle delays and percentage of stopped vehicles. Time is divided into intervals of 5 seconds. The optimisation procedure is performed, for each isolated intersection, through a dynamic programming technique looking for the control on a rolling horizon. The optimal strategy for the start of a particular stage is based on measurements from upstream detectors for the beginning of the projection period and the smoothed average flows for the end of the projection period [26,28,29].

Equipment-Hardware-Software

The OPAC-RT Version 2.0 system is composed of 3 major subsystems, the Data Acquisition and Control Subsystem, the Processor Subsystem, and the Traffic Signal Subsystem. The Data Acquisition and Control Subsystem performs two functions in the OPAC-RT system. First, it provides an interface between the processor and the signal controller and second, it collects traffic flow information for use by the processor in executing the optimisation algorithm. The detectors are located well upstream (120 to 180 m) of the stop bar on all approaches to an intersection. Additional detectors (call-only detectors) are placed at the confluences of driveways with the links.

The Processor Subsystem consists of an IBM-AT microcomputer running at 8 MHz and includes a minimum of 640 of main memory, at least one disk drive with a minimum of 600 available storage, and at least two available expansion slots. The Traffic Signal Subsystem includes a NEMA certified Eight Phase Dual Ring Digital Controller Unit, a NEMA certified

Conflict Monitor, and other equipment normally used in a typical cabinet set up.

The support software required to run and maintain the OPAC-RT Version 2.0 software includes the following:

- Version 2.0 or later of the MS-DOS or PC-DOS operating system.
- Version 4.01 or later of the Microsoft FORTRAN77 compiler.
- Version 4.0 or later of Microsoft Macro Assembler.
- Version 3.05 or later of Microsoft 8086 Object linker. (An overlay linker should not be used).
- Any text editor producing standard DOS text file format [26].

Facilities

OPAC provides traffic engineers with facilities such as tacticed detection, congestion override and modeling turning movements. These facilities are described below.

In OPAC, call-only detectors for tactical detection are placed at the confluences of driveways with the links. It is important that call-only detectors be present, since the OPAC detectors are located far upstream. Without call-only detectors, vehicles entering the traffic stream from driveways and shopping centers downstream of the OPAC detectors would not be detected. Without call-only detectors, even if there are not any vehicles waiting at the confluence of the driveway with the link, the system will assume there are vehicles waiting to enter the link and service them unnecessarily.

PAC provides an optimisation algorithm which may be overridden by special signal plans in the presence of congestion, as defined by a user-specified occupancy threshold. OPAC uses a special 'congestion override' facility, since the optimisation is intended for operation under normal (undersaturated) conditions. During periods of congestion, measures of effectiveness such as queue length might be preferable to stops and delay, used as optimisation criteria under undersaturated conditions. Moreover, during periods of congestion, queues may become extremely long, extending over the upstream detectors. As a result, traffic demand will not be accurately measured by OPAC. If the occupancy of the detectors associated with one of the major phases exceeds the threshold, the switching decision for that phase is ignored and the phase is allowed to time to its maximum. When the occupancies for that phase fall below the

threshold, the switching decisions from the optimisation algorithm are implemented.

The minor, typically left turning, phases are treated by OPAC-RT as part of the intergreen period. Hence, the software must have an approximate, if not exact, duration for each minor phase. Since the exact duration of the minor phases depends on the demand, the software maintains an exponentially smoothed value for the duration of each minor phase. These values are used by the optimisation algorithm as the current expected minor phase durations in determining the optimum termination points for the major phases.

Since the OPAC detectors are 120 to 180 m upstream of the intersection, left turning volumes are modelled by the software. To accomplish this, a smoothed, expected duration for each minor phase is maintained. Based on the current expected phase durations and user-input discharge rates, estimated volumes for each minor phase are calculated. The calculated volumes are assigned to the minor phases and the total volumes, adjusted for the vehicles expected to turn left, are assigned to the major phases [26].

Potential Facilities (under research)

OPAC has reached the point where industrial development is possible. Further research has been made in order to improve the algorithm, particularly on aspects relating to features designed to minimize the amount of fine tuning required by local traffic engineering personnel have been under research.

Research is evaluating the possibility of an OPAC configuration, with the video detection technology (Wide Area Detection System - WADS). WADS development is sponsored by the FHWA. This technology offers the potential of reducing the high installation and maintenance costs associated with loops detector. Other detection technologies, such as the self-powered vehicle detector, might also offer the potential for eliminating the high lead-in costs.

While research on OPAC to date has concentrated on the isolated intersection control, research has also been performed in implementing the method in a network context. The results from field tests 2 and 3 (described below) have shown the positive response of the OPAC-RT system to platooned traffic, which is typical of arterial and network systems. Since the results exhibited by the isolated intersection version were positive, arterial optimisation with OPAC can be expected to reduce the delay to drivers [26].

Effectiveness-Accuracy-Benefits

Three field tests of the real time OPAC traffic signal control system were conducted by FHWA. The first two were directed at the evaluation of the first version of the OPAC system, which was limited to the control of two phase intersections (OPAC-RT Version 1.0). Based on the observed performance of the first version, various enhancements were identified both to increase the effectiveness of the system and to permit installation of OPAC for control of a broad range of controller phasing configurations. After making the required modifications, the second version of the system (OPAC-RT Version 2.0) was evaluated during the third field test conducted at a site operating with an eight phase dual ring controller. The principle measures of effectiveness selected for comparison of the performance of an actuated controller and the OPAC systems were delay and percentage of vehicles forced to stop. The performance of the OPAC strategy was compared to the performance of the Econolite D2000 used as a fully-actuated controller.

During the first field test (conducted at the intersection of North George Mason Drive and North 16th Street in Arlington, Virginia), both delay and the percentage of stops were decreased when the intersection was under the control of the OPAC system. The improvements were modest; for data aggregated over intervals of approximately 10 minutes, delay was decreased, on the average, by 3.9% and stops were decreased by 1.6%. However, the observed volumes during this field test were extremely low. More definite statements regarding the performance of the OPAC system would require additional analysis of stops and delay at higher volumes.

During the second field test (conducted at the intersection of Flowing Wells Road and Prince Road in Tucson, Arizona), delay was greatly reduced under OPAC system control. On the average, delay was reduced by 15.9%, despite an increase of 4% in average volume. The percentage of vehicles forced to stop, on the other hand, was increased on the average by 3.9%.

Since stops were not an OPAC measure of effectiveness in the first version of the system, and since there was also an increase in volume during OPAC operation, this increase in stops was to be expected and represented a minor degradation in the performance of the OPAC algorithm, with respect to the actuated controller.

During the third field test (conducted at the intersection of Flowing Wells Road and

Prince Road in Tucson, Arizona), delay was decreased on the average by 7.7% at an eight phase intersection. However, despite the inclusion of stops in the OPAC system's signal timing optimisation function, the percentage of stopped vehicles was increased by an average of 9.5% [26].

Limitations

OPAC presents certain limitations regarding intersection coordination, estimating saturation flow rates, estimating queue length, and compatibility. A brief discussion of these limitations is presented here.

The system to date cannot coordinate sets of intersections; it is usable only for controlling an isolated intersection. While research on OPAC to date has concentrated on the isolated intersection control, some research has been performed in implementing the method in a network context. The results of the above mentioned field tests 2 and 3 have shown the positive response of the OPAC-RT system to platooned traffic, which is typical of arterial and network systems. Since the results exhibited by the isolated intersection version were positive, arterial optimisation with OPAC can be expected to greatly reduce the delay to drivers [26].

OPAC does not provide the traffic engineer with facilities estimating on-line saturation flow rates [26].

In OPAC, the objective function to be minimised is the accumulated expected queue at the intersections of interest. To estimate the queue length, arrivals are considered binomially distributed. The queue length evolution forms a Markov chain, leading to objective function calculations that require manipulation of large probability arrays. Such manipulation is inefficient in terms of computer time and storage. Several approximate methods for the calculation of the objective function are in good agreement with the Markov approach [21].

During a field test conducted in Tucson, Arizona by FHWA to evaluate OPAC-RT Version 2.0 system on an eight phase intersection, and despite the inclusion of stops in the OPAC system's signal timing optimisation function, the percentage of stopped vehicles was increased by an average of 9.5%. However, further calibration might lead to a decrease in the percent stops [26].

Finally, certain compatibility issues would also have to be resolved before OPAC could

be implemented in the U.S. For instance, implementation of OPAC within a standard 170 controller (commercially available, microprocessor based controller capable of implementing a traffic control strategy, as given in the microcode within its EPROM) or its successor, the type 179 controller, is not possible without several modifications to the controller and to the OPAC algorithm. These modifications would include a new processor, such as an Intel 80286 or a Motorola 68020, at least 640 of processor RAM, at least 640 of EPROM or EEPROM, which could be overlaid onto the system RAM if necessary, and a system clock that will provide a processor cycle time of 0.1 microseconds or less. A math coprocessor would also be required, unless the processor speed or efficiency is increased to compensate for the lack of the coprocessor. In addition, detectors for OPAC are farther upstream than current U.S. practice. Therefore, in order for OPAC to be installed in the U.S., the detectors would have to be replaced [28].

Applications

OPAC has not yet been implemented in the field. However, it is expected that research on the algorithm will soon lead to an industrial version.

II.3.5 MOVA

The Microprocessor Optimized Vehicle Activation (MOVA) methodology was originally developed to provide traffic control strategies for isolated intersections. The MOVA methodology developed and tested in Berkshire, England, by the Transportation and Road Research Laboratory, has led to control strategies that are substantially improved over the conventional vehicle actuation signal systems throughout England.

The control strategies include a more efficient use of green time when traffic is flowing at considerably less than full saturation rates. MOVA also contains self optimizing control capabilities in which the duration of the green time is optimized to reduce delay and utilize the available green time more efficiently during saturated conditions. MOVA is structured to optimize the green timings for the critical traffic movements on a phase by phase basis. Further, expanded library capabilities allow setting appropriate maximum green times to cover a wider range of traffic conditions for different times of the day, day of the week and season

of the year.

The following sections describe the detector layout, the MOVA microprocessor and the principles of MOVA control as presented through the TRRL Research Report 170 [31].

Site Layout For Detectors

All detectors used with MOVA have been limited to buried inductive loops. Such detectors provide lane-by-lane counts and information on the presence of vehicles. These data lead to estimates of flows, delays, stops and queue length. To accomplish this, two diamond shaped detectors are installed in each approach lane at 40 and 100 meters from the stop bar. (see Fig.1). MOVA calculates the vehicle travel time between the loops and the stop bar which is typically 3.5 and 8.0 seconds respectively based upon average vehicle speeds in urban areas. However, these values are not critical and location of the detectors is flexible provided that the algorithms reflect the actual length between detectors and the stop bar.

The detector farthest from the stop bar is called the "IN-detector" and the detector closer to the stop bar is called the "X-detector". The gap or time interval between detection of two consecutive vehicles is monitored at the X-detector, and is used to determine the reduction in flow below saturation and anticipate a phase change. The IN-detector provides additional information about approaching or queued vehicles and this leads to better recognition of over-saturated conditions. The additional information also allows better performance of the delay and stop minimizing process described below. The IN-detector is needed to assess conditions including approach volumes at approaches that widen out at the stop bar, a common practice for reducing queue length in England.

The 40/100 m detection system has certain disadvantages. Without detectors closer than 40 meters, vehicles that fail to clear the green after their arrival have a greater probability of remaining undetected and having to wait until another vehicle arrives to activate the detector. As a solution, a third detector can be included at the stop bar. The stop bar detector is also added when an exclusive right turn lane is needed for the right-turn only phase. (This is similar to the lagging left turn phase in the U.S.)

The MOVA Microprocessor

MOVA is based on a microprocessor that includes four primary software programs: Input Routine, Strategy Programs, Output Routine, and Archive Program [34]. The first program, "Input Routine", samples vehicle counts ten times per second and provides volume and occupancy data. The second, "Strategy Program", uses data from the first program to determine when a phase change is needed. When a phase change is necessary, this program calls the third program, "Output Routine", which instructs the signal controller to change the phase of the signal. The final program, "Archive Program", stores data for subsequent analysis. Implementation of a completely new strategy, requires revising the second program only. All programs are written in Fortran 66.

Within the signal controller cabinet, MOVA detectors are connected directly into the MOVA computer unit containing the four primary programs, not to the standard signal controller. The local signal controller is fitted with a standard Urban Traffic Control (UTC) interface that allows the MOVA computer to force the traffic signal to change phases. The controller sends signal status configurations to MOVA and MOVA returns phase-change commands.

Principles Of MOVA Control

During the green period, MOVA makes a number of decisions based upon traffic flow and queue information derived from the vehicle detectors placed within each approach. The decision to change phases is based upon minimum green calculations, determination of the end of saturation flow, optimization of delay and stops and oversaturated conditions [31]. For example, to facilitate the calculation of green time, MOVA assigns a stop penalty value to each approach that indicates the relative importance of stops to that approach. When the green phase at an approach is nearing the end, MOVA assesses the merits of extending it against the stop penalties accumulating from vehicles arriving and stopping at the other approaches. The assessment is based on a performance index that is similar to the TRANSYT performance index and is a function of delays and stops. Using the stop-penalty technique to determine the length of green time offers certain advantages over the classical vehicle actuation systems that use the gap-seeking control technique. In particular, the stop penalty technique considers the delay time

of waiting vehicles and does not extend green time unnecessarily during unsaturated conditions. This optimization technique is superior to the existing vehicle actuation system requirement of presetting maximum green times which are inefficient during unsaturated conditions.

An additional benefit of the MOVA system is the phase to phase flexibility with which the user can input preselected conditions as they would apply to various phase demands including eliminating particular phases within a cycle sequence. The major features of the MOVA decision process are described below in some detail [31].

Minimum Green Calculations

The absolute minimum green for a particular phase is defined by the user and is based upon reaction time expected of drivers and pedestrians within acceptable safety standards. During the red condition for a particular approach, MOVA counts the number of vehicles that pass over the X-detector for all lanes within the approach. After changing phases to the approach, MOVA estimates the minimum time needed to clear the queue between the X-detector and the stop line for each lane of the green approach. The approach minimum green time is then computed as the largest of the lane minimum green times for the group of lanes within the particular approach.

Determining End of Saturation Flow

MOVA examines the size of the time gap between successive vehicles as measured at the X-detector to determine the end of saturation flow for an approach. The approach is judged to be at the "end of saturation" condition as soon as any one lane of the approach is discharging traffic at less than the user defined preset saturation rate. This gap checking procedure involves comparing the current gap against a pre-defined critical-gap value, typically 3.5 s for the saturation rate threshold.

To determine the end of saturation for the current phase, MOVA checks the status of all approaches currently receiving green time. The gap of the vehicles on the primary approach of the intersection must be longer than the pre-defined critical gap before a phase change is considered. Approaches that are scheduled to receive green in the next phase are not classified as primary approaches. MOVA extends green time to the current green phase subject to preset

maximum green times until all primary approaches on a particular phase have reached the state of "end of saturation". TRRL research suggests that minimum delay is usually achieved if traffic discharging at saturation rate receives enough green to clear the queue completely [31].

Optimization of Delay and Stops

To optimize delays and stops, MOVA uses a model representing traffic flow on each approach lane. This model is updated by data from the IN and X-detectors every half second and represents both the predicted position and the movement of vehicles based upon the preset travel speeds between the detectors and the stop bar. Once traffic is moving freely on all primary approaches, MOVA estimates the number of vehicles on each green approach which would benefit from the extension of green time. Concurrently, MOVA maintains a count of vehicles queuing at the red approaches around the intersection. From these counts and the average arrival flows expected to join these queues, MOVA estimates the disbenefit which an extension of the current green would cause to the vehicles on the red approaches. In conjunction with the above computations, MOVA estimates how long traffic on the green approaches would have to wait for the signal to become green again during the next cycle if the current green were not extended.

The above computations provide an overall estimated delay savings that would result by extending the green time. Based on this estimate, MOVA calculates a performance index equal to the sum of the net delay and the weighted stops for all primary approaches of the intersection. MOVA changes the signal to the next phase if the performance index falls to zero or below; if the performance index is positive, the current green is extended.

MOVA methodology is designed to provide efficient green times. MOVA limits the individual phase green times automatically to achieve the desired cycle time limits. Maximum green times are set considerably longer than conventional timing because the maximum green is rarely achieved. However, at high volume sites, long term heavy flows may result in cycle times that are considerably longer than desired. At these sites, an upper limit to the cycle time is specified in order to allow pedestrian crossings and prevent upstream blocking of driveways and intersections that can result from queuing.

Oversaturated Conditions

MOVA recognizes an oversaturated condition as a situation in which one or more approaches are left with a significant queue at the end of the green time. MOVA automatically switches from the normal delay-and-stops minimization described above to a capacity-maximizing process that seeks to clear the congested approach as quickly as possible. The process of maximizing capacity is based upon the assumption that the signal timings that maximize capacity are similar to those that minimize delay.

This algorithm is based upon a relationship between the duration of the current green phase and the estimated durations of green time for the other phases making up the cycle. The estimated duration is based upon vehicle counts by the X-detector at the other approaches. From these data, MOVA estimates a flow efficiency factor which is computed every half-second. When the flow efficiency factor falls below the computed peak efficiency by a pre-set amount, the green time is ended and MOVA cycles to the next phase.

As discussed in greater detail in [31], MOVA includes a capacity-maximizing logic procedure. More scientifically, a particular link which is classified as "oversaturated" first receives the appropriate minimum green as usual. After the minimum green, MOVA doesn't check for the "end of saturation" but, rather, assesses the possible uses of the green time within a cycle and decides whether or not capacity is likely to be maximized by continuation of the green on the current phase. The capacity-maximizing process allows the green on an oversaturated approach to continue as long as the approach saturation flow stays constant through the green phase subject only to limits based upon public acceptance. Thus, the signal operates using long cycle times and minimizes the lost time wasted between phase changes. Typically, during the green phase, the rate of discharge from a link is high initially but decreases later. MOVA assesses whether capacity would be maximized by ending the green as soon as the discharge falls below the initial saturation flow value, or whether it may be better to continue the green despite the reduced rate.

MOVA operates on a relatively short cycle length for congestion at approaches that widen at the stop bar. Short green times allow the method to take advantage of the initially high saturation flow discharges from the approach to dissipate the queue.

II.4 Conclusions

This chapter reviewed the optimization methods and system configuration of the state-of-the-art strategies developed for intersection control. SCOOT is based on centralized methods in performing optimization, whereas SCATS performs much of the optimization procedure in its vehicle-actuated controllers. PRODYN and OPAC perform the optimization at each intersection using dynamic programming techniques. OPAC tries to minimize vehicle delays and percentage of stopped vehicles and PRODYN attempts to minimize total delay. In OPAC, detectors are located far upstream of the stopline, while PRODYN requires two detectors at upstream and near the stopline. SCOOT and SCATS have been implemented in the urban traffic control systems of many cities worldwide and have demonstrated their ability to coordinate large arterial and grid networks. By contrast, PRODYN and OPAC have been implemented only for evaluation purposes on small networks. Finally, MOVA, an on-line signal optimization package, developed in Berkshire, England, by the TRRL, is also reviewed in this chapter. It tries to improve efficiency and capacities at signalized intersections while reducing stops and delays. Its application has been limited to isolated intersections since the control algorithm can handle only phase split and cycle length adjustment. MOVA does not allow offset evaluation, a capability that would be required for the coordination of signalized intersections.

III. EXISTING OPERATIONAL SYSTEMS FOR INTERSECTION CONTROL

III.1 Introduction

In order to meet the needs for efficient traffic management, certain municipalities have developed their own control system for interconnected signalized networks. Leaders in this area include the cities of Minneapolis, Minnesota; Los Angeles, California; and Toronto, Canada. This chapter reviews intersection control strategies currently in operation at these cities. The following sections summarize detection and control methods of each system.

III.2 MINNEAPOLIS, MINNESOTA

III.2.1 System overview

The City of Minneapolis presently has 760 signalized intersections, of which one-third are actuated and two-thirds are pretimed. Within the citywide network, 710 or 93% of the signals are centrally controlled via a centrally-supervised, digital computer based traffic control system. The central control is monitored by a modified T-200 Traffic Control Program software system developed by Traffic Control System, Inc., now Fortron Traffic Systems, and installed in the mid 1970's. Presently, there are four types of intersection controller equipment (Type A, B, C and D) depending upon whether the coordination procedures and signal turning plans are stored at the intersection controller and monitored by the master controller or whether the coordination procedures and signal timing plans are stored at and operated by the master controller.

There are three main states of operation for the signal controller, namely offline, local and computer control. The methods of system operation include a master controller supervision technique with coordination units for pretimed and actuated intersections and master computer issued yield-force-off control on those intersections without coordination at the local controller. Multiple Split Intersection Control (MSIC) and Bus Priority Operation (BPS) provide phase split adjustment under coordination of the master controller. The system has recently been updated to improve the system communications, provide for greater equipment flexibility and allow bus priority operation. The following is a brief summary of the existing T200 Traffic Control System as detailed by the City of Minneapolis [40,41].

III.2.2 Control system description

Master Controller

The T200 system is a single user, real time traffic control system controlling and monitoring all system intersections once per second. The master controller is a centralized digital computer. The main master computers are two MODCOMP IV-25 cpu with 80k x 16k bit words of core, each expandable to 128k x 16k bit words. The control console consists of one CRT and one TTY. The control console includes an emergency override, test equipment monitor, map power and testing device. The CRT and keyboard are used as the primary input and output device. Interconnected at the master control center are four test signal controllers which represent each of the four categories of signal controllers (see Section 2 used in the system. These units are used to test repaired control communication devices and signal-controller-related software in a safe environment.

The master computer can monitoring the operation of all intersections within the network, regardless of control mode of the signalized intersection controller. The master computer is also capable of commanding intersection controllers to change from the local-control mode to master computer control mode to use computer generated timing plans.

The master controller continuously monitors system performance parameters including volume, occupancy, speed, delay, stops and que length at the signalized intersection. When an intersection within the system exceeds the threshold for a particular parameter, the operator is notified and the appropriate system modifications are made either automatically or manually.

Intersection Controller and Detector Equipment

The intersection signal controllers are either pretimed or locally actuated devices. Each controller contains an adapter that enables it to accept digital data over the communications network from the master controller. The mix of signal control equipment includes 78% fixed time with the remainder either actuated controllers with coordination units tied with the master controller or isolated actuated controllers. Controller equipment varies in age, make and timing method and includes electro-mechanical, digital and analog timing devices.

All controller equipment, regardless of make or manufacturer, is assigned, for system control purposes, to one of the following four categories depending upon whether the coordination procedures and signal turning plans are stored at the intersection controller and

monitored by the master controller or whether the coordination procedures and signal timing plans are stored at and operated by the master controller.

- Type A - non-actuated with supervision from the system master controller.

- Type B - semi-actuated controllers supervision from the system master controller. This controller provides phase skip capability. Unit extensions for the actuated phase are controlled by the system master controller.

- Type C - semi-actuated controller with operation of the coordination unit by the system master controller. All phase skipping and unit extension capabilities are retained at the local controller.

- Type D - actuated isolated controller without a coordination unit. The system master assumes control of the coordination unit by enabling the semi-actuated features of the controller when the -"Hold-On-Line" signal is issued. The controller rests in main street green until the proper phase split has been timed whereupon it yields to local secondary phase demand. Maximums are specified from the system master controller by force off commands, returning the controller to main street at the proper time to maintain cycle offset and phase split. Phase skip and unit extension capabilities are maintained at the local controller.

In Type A, B and C controllers, operation equipment status and main street green signals only are monitored. In type D controllers, all greens are monitored.

Detector layout generally conforms with the ITE recommended practice for actuated and activated control. Data from each detector and pedestrian button in the system is transmitted to the system master controller for system usage and equipment monitoring. At actuated equipment locations, detectors are connected to the signal controller which in turn, return data to the master controller. New detectors are located for system traffic response, count, Multiple Split Intersection Control (MSIC) operation (see Section C) and Type B local controller operation. Detector equipment includes 10% magnetometer and 90% inductive loop detection equipment [40].

Software

The traffic control system consists of a MODCOMP MAX III operating system and Computer Systems Engineering's T-200 traffic control programs [41]. The T-200 system provides various control capabilities. Initially it controlled the operation of traffic signal

controllers; with expansion, it now includes the addition of changeable message signs. Provisions currently exist within the communication system to accommodate changeable message sign control. Fundamental provisions have been made in the system for this addition of sign control software and necessary memory expansion facilities. City personnel have incorporated existing signal installations by modifying the intersection controller to transfer digital data to and from the master controller, thus able to utilize the in-place detectors and hardware at the intersections. The T200 system consists of a master controller capable of monitoring all intersection controllers within the network.

Communications

The communications network consists of telephone type cable installed in conduit throughout the City. The network is arranged into communication subgroups with a dedicated and spare pair provided to each group of up to 14 intersections. A common circuit is provided to all locations within the system. Splices, terminations, and cross connections are made on telephone type terminal blocks.

The communications system consists of a Central Communications Multiplexer (CCM) at the master controller and the cable network. The CCM consists of a rack mounted printed circuit card assembly and is interfaced to each of the active communications circuits. Communication and basic interfacing to equipment at the intersection is handled through a modularly constructed unit installed at each intersection called, Communications Modification Unit (CMU).

The CCM sends and receives a message to and from each CMU in the system once per second. The CMU interfaces the communication lines to the computer through eight Line Driver Receiver Modules (LDRM). Data is transferred to each communication line and each CMU connected to that line at a rate of 2016 bits per second. The message is received at each CMU but only accepted at the specifically addressed CMU location. The CCM receives information in response to CMU generated signals. Messages received by each LDRM are transferred to the CCM storage area, error detection procedures applied and the data transferred to the CPU.

III.2.3 Control modes

The system has three states of operation for the signal controller; offline, local and computer control. Under the OFFLINE state the master computer equipment may be operational but field equipment is locked into a condition uncontrolled by the master controller. Under the LOCAL state master computer equipment is operational and field equipment is designated as ready for pick-up. Under COMPUTER CONTROL field equipment is operating under control of the master computer. Each of these operating states is scheduled with an individual intersection or group of intersections.

Two basic methods of system operation provide effective control of the full range of traffic signal controller equipment used in the system. The methods used include a system master controller supervision technique on motor driven intersection controllers together with coordination units for pretimed and actuated intersections; and system master computer control on those intersections without coordination at the intersection controller.

Two special control techniques provide phase split adjustment under control of the master controller. The techniques are identified as Multiple Split Intersection Control (MSIC) and Bus Priority Operation (BPS).

MSIC operation is a special form of traffic responsive control which provides for split adjustment on a cycle by cycle basis, i.e., special control operation of certain critical intersections in the system. MSIC operation is automatically selected at an intersection based upon congestion levels at that location. This form of operation can be applied to any intersection with appropriate detector layout which includes all approaches and at the stop bar.

The Minneapolis BPS operation is a special form of semi-actuated control and can be applied to any intersection with suitable detectorization 30 feet upstream of the intersection within the bus lane approach. When a bus is detected the green time of non-bus movement is reduced providing an early green to the bus movement. The amount of split variation is under full control of the master controller and may, therefore, be as much or as little as deemed appropriate by the traffic engineer for any particular time of day. The net result of this technique is to maintain offset control for beginning of the green phase for the non-bus movement.

The scheduling mechanism for the Minneapolis traffic control system consists of

individual entries for each intersection containing both time-of-day related direct control information and indirect traffic control information related to each intersection's operation.

The primary technique for arranging groups of intersections is the lead intersection arrangement. This entry permits one intersection to duplicate (or copy) the schedule entries of other intersections within the group.

Provisions within the system enable extensive monitoring of system performance and hardware operation. Data are returned from each of the detectors and controllers in the system to the system master controller where all data are tested for validity with errors noted and logged. Valid data are used to provide system records, measures of effectiveness and inputs to the traffic responsive portion of system software. Performance data are made available to the traffic engineer upon request and depending upon its type, is displayed on the system map, system CRT or are printed as hard copy records.

The operation of all hardware including controllers, detectors, and communications equipment is monitored to ensure that each component is performing properly in relation to issued commands and expected responses. If a device is determined to be operating improperly the unit is declared automatically by system software to be either controlled through another mechanism or unusable within the system. This information is logged, recorded and corrected as soon as possible.

II.2.4 Operator Interaction

On-line operator interaction with the system is provided by several devices at the master controller through a special software package. The devices include the control console, the operator's CRT, the logging printer, the report printer and the system display map.

The control console provides several functions including emergency override switching of the traffic control system to manual control operation, manual control of message sign system operation, audiovisual notification of a log report, and monitoring of the test controller operation. This device is intended to provide simple uncomplicated direct interaction with the system.

The operator's CRT and keyboard, through the special software package called TELAN

(Traffic Engineering Language), is the primary interactive element of the system. All interrogative and declarative activities are processed through this combination of facilities. Requests for information and commands to execute an operation are entered in English using the keyboard. In each case this entry is shown on the CRT. The important TELAN command statements include SHOW, PRINT, CHANGE, ADD, and DELETE. All data bases and files are accessible and changeable on-line. All reports may be requested, shown and printed on-line.

III.2.5 Future plan

The central computer hardware, traffic control software and communications system capacity was expanded by mid 1992. This expansion improved the system communications, expanded equipment selection flexibility, and allowed bus priority operation. System capacity will be expanded from 760 intersections to 990 intersections and 1200 detectors to 3000 detectors.

III.3 LOS ANGELES, CALIFORNIA

III.3.1 System overview

The City of Los Angeles includes 3900 signalized intersections within the city street network. Of these, 747 are pre-timed and centrally controlled through a network system called Automated Traffic Surveillance And Control (ATSAC). With this system, various timing plans automatically respond to fluctuating traffic demands on a real time basis. Key subnetworks within the ATSAC system include the Coliseum, Central Business District, Ventura Boulevard (west end), Westwood I, Harbor Freeway Corridor, Ventura Boulevard Zia (east end), West Los Angeles and the Airport [38].

A L.A./DOT study of signalized intersections presently under ATSAC control showed significant benefits over the previous pre-timed, independent system. The study showed that vehicular stops were reduced by 35 percent, intersection delay reduced by 20 percent, travel time reduced by 13 percent, fuel consumption reduced by 12.5 percent and air emissions reduced by 10 percent. The benefit-to-cost ratio was accounted at 9.8 to 1 revealing that the system paid for itself within one year [8].

The discussion which follows includes highlights from a report completed by the Los Angeles Department of Transportation [39].

III.3.2 Control system description

The ATSAC system includes a control console and supervisory (main) computer at the control center, subarea computers and front end processors at the central subarea centers, and traffic signal controllers and loop detectors at the intersections. The main computer monitors traffic development and chooses the optimum timing plan for each level of traffic. The plan is selected from a group of 30 timing plans for each intersection or group of intersections. The timing plans include a.m. peak, p.m. peak, off peak and modifications of each of these depending on the day of the week or a special event.

Computers and Software

The main central control computer is a Concurrent Computer System 3280 configured with 16 megabytes of main memory. This computer provides the interface between the system computers in each network subarea and the rest of the central system equipment. Each ATSAC subarea includes a Concurrent Computer System 3280 mini-computer with 10 megabytes of main memory. This computer is capable of handling up to 400 intersections with 1600 detectors within the subarea. The central computer communicates with the subarea computer over an Ethernet network which has an effective data transfer rate of 50 K bytes per second. Each subarea computer has a front end peripheral processing unit (PPU) that assists the processing of data accumulated from the large number of intersections and detectors within the subarea.

The application software used with the ATSAC system is the UTCS developed by the Federal Highway Administration. The UTCS Software is enhanced under the ATSAC system to include color graphics, display monitors, a supervisor/subarea computer network, network for communicating signal plans to local signal controllers, and automation of signal plan updates.

Communication of data between the ATSAC control center and the subarea computer near the center of each ATSAC subarea is performed with fiber optics cable which is suitable for both video and traffic control surveillance data. Data from the subarea computer hub to

each intersection controller within the subarea are transmitted over a 1200-Bd twisted pair telephone cable network. This network is also used for the communication of the traffic data and equipment status from the intersection controller back to the subarea computer.

The Type 170 controller is used at all ATSAC intersections, equipped according to Caltrans standard requirements. For on-line signal controllers, the subarea computer monitors the intersection controller through each signal phase. Volume counts and occupancy data are initially processed by the signal controller and transmitted to the control center via the subarea computer once per second. The intersection controller uses backup plans stored in its local memory when it operates off-line or when it is at a standby status. Each intersection signal can store up to 9 off-line timing plans for that intersection.

Loop Detectors

ATSAC loop detectors are located on the major legs of signalized intersections, 250 feet in advance of the intersection. The data acquired by the advanced detector include volumes, saturation, occupancy, speed and queue length.

At intersections of arterial streets and local streets, the signal is semi-actuated, controlled with detectors on the local street only. Traffic data from the local street are sent to the control center for monitoring. A+ intersections of major arterial streets, the detectors are placed upstream of each approach lane. Detectors can be laid out in two possible configurations. Following one configuration, detectors are placed within each marked approach lane at least 250 feet upstream of the signalized intersection; alternatively, detectors are placed 100 feet downstream from the nearest signalized upstream intersection. The second method is more economical since it places the detector closer to a signal controller box and, therefore, requires less detector wire and conduit. However, this method is used only where no significant additions or losses of traffic occur between the detector and the downstream intersection, and where distances between intersections are not long.

Video observation

The City of Los Angeles is presently installing video observation cameras at 38 intersections; these include junctions for regional shopping centers, sports arenas, major crossroads, airport area and critical interchanges with the interstate system. The ATSAC

operator can visually detect accidents, disabled vehicles, spilled loads, construction activity and police and fire operations and implement an override timing plan if necessary. This is accomplished by installing a video camera 45 feet above the intersection on a pole or nearby building providing a 1/2 mile wide overhead view of the two intersecting streets.

III.3.3 Control modes

Four modes of control are available in the ATSAC system, depending on the time of day, volume of intersection traffic, location and type of intersection. The four modes include Time of Day Control, Critical Intersection Control, Traffic Responsive Control and Manual Override [39]. Time of Day Control mode includes timing plans developed off-line using the TRANSYT VII model and manually acquired traffic data and turning counts. Three to nine timing plans are available per intersection including a.m. peak, p.m. peak, off-peak and modifications of each, depending upon the day of the week or a special event. Once on-line, signal offsets and splits are fine tuned by the ATSAC operators.

The Critical Intersection Control mode operates on a real time algorithm that modifies the cycle green time split at signalized intersections. Detectors are required at all approaches for this mode. Traffic demand equations are updated at each cycle, and green time is prorated to each approach based upon relative demand, i.e., volume and occupancy. The range of green time modifications is limited by the minimum pedestrian clearance time. Signal offset is maintained on the major street causing performance degradation on the secondary street. This mode automates the process of modifying the allocation of green time in response to changing traffic conditions along the main street and eliminates the manual override procedure for fine tuning signal splits on a regular basis.

The Traffic Responsive Control mode uses the automated functions of the UTCS Enhanced software. Timing plans available to an intersection controller are computed using historical traffic data. A specific timing plan is selected by comparing and closely matching the real time surveillance data with the historical traffic data. This method is a major improvement over Time of Day mode in which day to day variations are significant. Extreme errors from implementing erroneous timing plans are prevented by limiting the number of available timing plans for a particular time period or day.

The Manual Override mode provides greater responsiveness to non-recurring traffic conditions. This mode can be implemented at a single intersection or group of intersections along an arterial route or within a particular area. This mode is operator controlled and activated during special, non-regular events such as special events at the Coliseum, holiday season traffic, major construction projects, temporary lane/street closures, diversion of traffic from a freeway, or to assist the traffic flow past an accident at a critical location.

III.3.4 Future plan

The City anticipates the addition of 177 intersections which include the subnetworks of Hollywood 1, Hollywood 2 and Victory Corridor West. An additional 558 signals within Ventura Corridor 2B, Victory Corridor East and Santa Monica Freeway Smart Corridor are presently designed for implementation into the ATSAC system. L.A.DOT seeks to connect the design of all signalized intersections to ATSAC by 1996 with implementation to follow in 1998.

ATSAC operators are currently developing and implementing the 1.5 Generation Control Strategy in order to fully utilize the on-line computer capabilities [39]. The present system requires operator intervention for developing a new system-wide timing plan when traffic flow data have changed significantly to warrant new area-wide signal timing plans. When implemented into the ATSAC system, the 1.5 Generation Control Strategy will automate the updating process of the traffic signal timing plan. The new software will use volume count data derived from the detectors, calibrated formulas that provide estimates for lanes without detectors, and estimated changes in turning volumes. The system will update the UTCS traffic control database utilized by the main computer and create a new timing plan using the TRANSYT VII model. The new timing plan will be sent to the appropriate signalized intersection via the established communication network.

III.4 Toronto, Canada

III.4.1 System overview

The City of Toronto has a total of 1641 signalized intersections with 1585 signals operating within a centrally controlled coordinated system developed approximately 30 years ago. Of

these, 686 signals operate in a fixed time mode and 899 are semiactuated [37].

Traffic data (vehicle presence) are collected with inductive loops located at the stop bar and left turn lanes. Each traffic signal system can support a 12 phase cycle, a specification more powerful than the typical 8 phase cycle in other U.S. system. Of the semiactuated signals, approximately 100 are truly actuated; they allow both pedestrians and vehicles to communicate with a particular phase and extend the minimum green time. The remaining signals are activated by the presence of vehicles but do not allow extension of green time. This centrally controlled system has a capacity for 64 cells within the network and 32 intersections per cell. The signal controllers for each intersection are inter-connected into cell groups. Each controlling intersection within the cell group is connected to the central controller. The central controller monitors the progress and status of each signal to ensure proper timing, phasing and cycle offsets for that signal.

III.4.2 Control modes

The timing of the cell groups is based upon historic traffic data, i.e. manual traffic counts including turning movements. Based on this information, signal timing, cycle length and cycle offsets are determined and adjusted. The main controller retains three primary cycle settings, a.m. peak (6:30 - 9:30), p.m. peak (3:30 - 6:30) and off-peak. Thus, the Toronto system operates on pre-set timing, not real timing.

Capacity problems are the basis for modifying a pre-set timing plan. When a saturation problem occurs on a fairly regular basis, city staff acquire traffic volume counts and recomputes the timing plan. If the saturation effect spills over into adjacent signalized intersections, the cycle length of these intersections is reviewed as well. The result is a delayed-traffic responsive system. Although the system can change timing plans every minute, it lacks the real time detector data, and therefore, relies mainly on the three preset timing plans described above.

III.4.3 Future plan

In 1990, the City of Toronto began implementing a demonstration project including the installation of a SCOOT system. The implementation is scheduled for completion by the end of December, 1992, with system review and evaluation by mid year 1993.

Seventy-five intersections within three different operational control areas will be under SCOOT control. The first control area includes 42 intersections within a grid network of the central business district. The second, includes 20 intersections along a controlled access arterial route that operates parallel to the freeway system known as Gardiner Expressway. The third control area includes 13 intersections along an uncontrolled access arterial. The three areas were chosen in order to evaluate the benefits of SCOOT under various types of operation and road environment conditions. The City of Toronto is implementing an Urban Traffic Control System that will operate the three control areas under either a fixed time mode (present operation) or a SCOOT mode. This will allow the city staff to conduct before and after field surveys to determine the benefits of SCOOT operation [37].

The city personnel have indicated that they prefer SCOOT over SCATS because SCOOT offers flexibility in adjusting the cycle offsets and accounting for traffic flow patterns in the overall system network. Their research concluded that a SCATS system would allow a flexible offset adjustment and that SCATS was better for optimizing individual intersections rather than system networks.

III.5 Conclusion

This chapter reviewed the current intersection control strategies and data collection methods of the three major cities in the U.S. and Canada. The Toronto system operates on a pre-set timing plan with the main controller retaining three primary cycle settings. In Minneapolis, the master controller monitors the operation of all intersections and overrides the local controller if necessary. The Los Angeles system selects a timing plan for each intersection in real time from a group of 30 timing plans depending on traffic volume. The following table summarizes the comparison of the three systems described in this chapter.

	Minneapolis	Los Angeles	Toronto (w/o SCOOTs)
1. System Master Controller	yes	yes	yes
2. Intersection Call Groups	yes	yes	yes
3. Pavement Loop Detectors	yes	yes	yes
4. Preset Timing Plans	yes	yes	yes
5. Real Time Algorithms	yes	yes	no
6. Bus Priority Operation	yes	no	no
7. Video Observation	yes	yes	no

IV. CURRENT DEVELOPMENTS IN VIDEO DETECTION

IV.1 Introduction

Video detection can improve the detection of vehicles at approaches to a signalized intersection. This system, presently on a trial basis at intersections in the Minneapolis, MN, metropolitan area and Oakland County, MI, can partially replace the wire loop detectors that are embedded into the pavement. System installation includes Trunk Highway 65 in Blaine, MN, and Oakland County, MI. This system requires a motion sensitive video camera for each approach. Presently, the video detection system can detect vehicle motion, vehicle presence (for left turn lanes) and vehicle speed [42]. The detectors are graphically laid out on the video screen and sense object movement past an established point on the screen. The detector layout must be adjusted for the camera angle and distance distortion to ensure proper detector placement within the particular lanes of an approach. The maximum range for video detection is approximately 400 feet from the intersection. At longer distances, the video camera cannot detect spacing between vehicles and this results in a false count, higher than actual conditions. However, where only limited data such as approaching platoons or merely presence detection is required, detection at lengths greater than 400 feet is acceptable. When placing the detectors on the video screen, it is beneficial to the user if a station grid is laid out on the pavement surface to provide a sense of real distance.

Thus far, the video detector method has been operating off line and the results compared to actual loop detectors in the field. Comparison of the two data sets are very favorable. Weather does not have a significant impact on the field camera. However, bright sunny days are better than cloudy, rainy days. The latter results in darker vehicle outlines which tend to "melt" into the shadowy background of the road pavement. Darkness is not a problem in that the camera is sensitive to the headlights, thus eliminating the impacts described above for cloudy weather.

Video detectors installed at intersections operate only for detection of vehicles at one approach. Essentially completing the same function as wire loops detectors. This type of system can be coordinated to operate under any existing signal control system condition including phase splits and cycle times as the wire loop detector. The capabilities of this system

will be expanded to detect presence of waiting and approaching queues, and provide immediate visual data of the intersection operations. The latter could enhance detection of stalled or parked vehicles blocking lanes at the intersection and prompt the master controller operator to direct traffic around the lane blockage.

V.2 System capabilities

A video detection device, developed in Minnesota, includes 4 cameras that can be handled simultaneously with full detection capability on each camera and up to 48 detectors per device with no loss in video processing. A directional detector was developed that operates only when vehicles move over it in the desired direction. A field of view calibration was added to assist proper sizing of detectors and to automate speed calculation. A loop compatible output module for the device that meets NEMA TS/1 specifications was developed, tested, and deployed to be electrically compatible with controllers and to provide the correct contact closer characteristics during system operation and when the system is not operating.

IV.3 Criteria for selecting intersections for machine vision control

This section includes the criteria for selecting an intersection for machine vision control. The reasons for selecting machine vision control at intersections are several. The first is flexibility in reconfiguring detector locations, a requirement for minimizing lane blockage (as, for instance, when loops are installed or repaired). The second is unsuitability of the pavement for loops (rough or broken pavement or on bridge structures), and cost effectiveness (when many loops can be replaced or eliminated and life-cycle costs reduced). Additional benefits can result from the ability to display the video from the intersection at a centralized traffic management center and to collect statistical traffic data for planning purposes.

Selection of first intersection on which to evaluate the machine vision detection system for application to a network or major arterial installation should consider the following factors: The intersection must be typical of those where further installation is anticipated and must include many lanes. Use measurements from existing loop detectors or other detection systems to verify and compare the accuracy and reliability of the video detection system, and prove that it meets the performance requirements. Finally, the intersection site should provide a variety

of camera placement alternatives for the initial installation and adequate volume demand during expected times of testing. (Testing should be performed around the clock in all types of local weather conditions.)

IV.4 Deployment procedure for the video detection system

Once a site has been selected, in cooperation with the authorities, a number of engineering tasks should be followed, prior to actual installation, and deployment of a video detection system. In particular, the site engineering for the video detection system is different from that which traffic engineers have experienced in the past. However, the engineering concepts are easy to understand and implement. One of the most powerful impacts of the technology is the human visualization and verification (instant feedback) that a video detection system can provide. The order of engineering tasks for deploying a video detection system generally follows these steps :

1. **Identify desired control strategies** prior to initiating the video detection system site engineering.
2. **Define the interfaces between the controller and video detection system** so that they are electrically compatible and reliable, and provide the correct contact closer characteristics during system operation and when the system is not operating. For example, a loop compatible output module for the video detection system that meets NEMA TS/1 or TS/2 specifications will interface satisfactorily to most controllers in North America.
3. **Thoroughly understand the detection requirements of the application** to be performed, i.e., where detectors are needed and what type (volume, occupancy, speed, gap times). Determine whether detectors should be tactical or strategic for use within an expanded signalized network of intersections. Determine whether the detector output calls are to be locking or non-locking.

4. **Update site drawings of existing sites to reflect "as built" dimensions.** Dimensions of most interest include, accurate placement of stoplines from the nearest corner; data on existing poles in the vicinity and pole coordinates with respect to road; and height on the poles where cameras can be safely mounted without interfering with road infrastructure such as power lines and phone lines.
5. **Define a detector placement configuration strategy that determines the expected field of view of the camera.** Certain detectors and detector information are typically more important than others in the configuration. It is important to understand which detector functionality may have to suffer due to geometric road considerations, such as safe placement and easy access to poles for maintenance, and absolute stopline detection to enable safe turning movements. Knowing the priority of detection needs makes it easier to choose optimal camera locations.
6. **Take advantage of existing infrastructure if possible, e.g., use existing poles, span wires, underground conduit, and cabinets.** When new equipment must be installed, providing for public safety and easy maintenance access is necessary. Check to see if capacity for video and power cables exists and if so, whether it is adequate for system requirements.
7. **Define a camera location and height that minimizes the field of view obstructions and vehicle occlusions based on the camera location and perspective.**
 - a. Increasing the camera height reduces the occlusion effects. Drawing simple diagrams of camera height, number of lanes of coverage, pole distance from the road, and expected vehicle heights from occluding lanes can typically help define a required camera height.
 - b. Camera placement should minimize reflections from leading headlights and adjacent roads at night. Leading headlight reflections can be eliminated by observing vehicles moving away; this, however, results in unrealistic and expensive "extra" pole placements at intersections. As an alternative, headlight reflections can be

minimized by placing detectors in closer along the lane proximity to the pole thus reducing the amount of reflected light that enters the camera. For example, cameras on poles placed adjacent to the stopline, at the same approach, optimize the field of view for high accuracy stopline detections (volume and occupancy) and minimizes leading headlight reflections which can cause false detections. Luminaries at the intersections also provide excellent occupancy results at night.

8. **Define camera synchronization and cabling requirements at the intersection.** Video systems that use line power for synchronization eliminate the need for separate synchronization cabling. When line power is used, it should be noted that electrical power must be supplied to the cameras from the same power and phase. This is easy at intersections since all cabinet and peripheral equipment is typically powered from a single source to the controller cabinet. Likewise, black and white video requires fewer cables than color video. Video cable loss should be accounted for if excessive cable runs are required. Typically, cables and cable connectors provide the most problems during video detection system installation.
9. **Define the fixed focal length optics based on the selected camera pole position and height.** Optics manufacturers provide field of view calculators (a hand-held device much like a mathematical slide rule) that simplify selection of the correct optics for the camera being deployed.
10. **Define locations and quantities of other peripherals used to route video and power cabling** between the video detection system (placed in the controller cabinet) and each camera on a pole. Additional needed equipment includes camera housing, camera pole mounting brackets, camera pedestal or mast arm, electrical and video service breakout junction box at the top of the pole, video coaxial cable, video input panel consisting of video lighting arresters and video ground isolation transformers for each camera, and a NEMA-rated controller cabinet to house the video detection system and controller equipment.

11. **Specify good video cable, connectors, and crimping tools.** This is important for reliable video communication between the cameras and the video detection system.
12. **Adequately train installers.** Training for hardware installation and maintenance, particularly for video cable and connector installation, is important. Training in detector layout and detector data file management should also be included. The traffic engineer may want to retain the video detection system developer under a continuing engineering contract to train installation technicians and engineers, quickly resolve installation problems and issues, define optimal detector placements for the best road coverage for each intersection, assist in programming the video detection system detectors, and troubleshoot interface problems with the controller.

IV.5 Conclusions

This chapter briefly reviewed the video detection system developed in Minnesota. The system is currently being operated in Minneapolis and Oakland County on a trial basis. A single system can include 4 cameras that can be handled simultaneously with full detection capability. The current video detectors installed in the test site has the same function as loop detectors, while its function will be expanded to detect presence of waiting and approaching queues, and to provide immediate visual data of the intersection operations. Appendix A summarizes the generic technical specification which covers requirements for real-time vehicle detection, measured or derived traffic parameters, hardware electrical and environmental performance, software capabilities, camera requirements, and interface requirements.

V. CONCLUSIONS

The most advanced concept for signalized network management employs demand-responsive control using on-line timing generators with adaptive control features. Software developed for this type of control include SCOOT, SCATS, PRODYN and OPAC. While there have been individual tests of each software by various agencies, no comprehensive effort has been made to evaluate and quantify the performance of the state-of-the-art control software, especially in terms of their applicability to detection both with loops and video image processing. In this research, the state-of-the-art software developed for signalized network control were reviewed and their advantages and limitations were analyzed. With the lack of field evaluations that can directly compare each software, this study focused on the review of theoretical principles and implementation issues found from the literature.

SCOOT and SCATS try to adjust the cycle time according to the level of congestion estimated on-line, while PRODYN and OPAC attempt to find the optimal acyclic settings where the signal timing is constrained only by minimum and maximum green times without requiring a fixed cycle time. The optimization indices for SCOOT and SCATS include stops, delays and queue length, whereas PRODYN tries to minimize delays. In OPAC, delays and percentage of stops are minimized. In SCATS, the phase split optimization is largely performed in its vehicle actuated controllers at local intersections, while SCOOT is based on centralized methods. Further, PRODYN and OPAC perform optimization at every intersection using dynamic programming techniques. SCOOT, SCATS and OPAC require one detector for each link, whereas PRODYN uses two detectors located at upstream and near the stopline of each intersection. In SCOOT and OPAC, the detectors are normally placed far upstream from the intersection stopline, which allows queue estimation. The detectors for SCATS are located at the stoplines. With a single detector located either upstream or at the stopline, it is difficult to monitor platoon progression in SCOOT, SCATS and OPAC. Further, SCATS can be implemented only on a special hardware, while other software have less restrictions in terms of hardware. SCOOT and SCATS have been implemented for urban traffic control in many cities worldwide and have demonstrated their ability to coordinate large arterials and grid networks, whereas PRODYN and OPAC have been implemented only for evaluation purposes

on small networks. Finally, MOVA, an on-line signal optimization package developed by the TRRL was also reviewed in this study. The current version of MOVA can handle only phase split and cycle length adjustment without allowing offset evaluation. Therefore, its application has been limited to isolated intersections.

In addition to the above state-of-the-art software, this study also reviewed the current operational intersection control systems in the major cities in the U.S. and Canada. More specifically, the urban network control systems in Minneapolis, Los Angeles and Toronto were reviewed and their control algorithms were presented. The Toronto system operates on a pre-set timing plan with the main controller retaining three primary cycle settings developed off-line for morning, evening peaks and off-peak. The timing plans are based on historical traffic data. In Minneapolis, the intersection signal controllers are either pre-timed or locally actuated devices. The master computer monitors the operation of all intersections within the network and can command each controller to change from local control to master computer-control mode. The Los Angeles system consists of both pre-timed and centrally controlled intersections. For each centrally controlled intersection, a timing plan is selected automatically from a library consisting of 30 timing plans. The main computer at the control center monitors traffic development and chooses the optimum timing plan for each level of traffic.

For further phases of this research, the following research directions were identified:

- 1) Comparison of the performance of the state-of-the-art control algorithms in the simulated environment,
- 2) Development of the live laboratory including loops and video detectors to test and evaluate the performance of intersection control software,
- 3) Development of optimal strategies and efficient algorithms for on-line intersection control,
- 4) Extension of the intersection control strategies to arterial network control.

ACKNOWLEDGEMENT: This research was supported by the Center for Transportation Studies, University of Minnesota. The Minnesota Department of Transportation and the City of Minneapolis are acknowledged for their support.

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APPENDIX: TECHNICAL SPECIFICATION

MACHINE VISION VEHICLE DETECTION SYSTEM

1. GENERAL

This Specification sets forth the minimum requirements for a system that monitors vehicles on a roadway via processing of video images and provides detector outputs to a traffic controller.

1.1 SYSTEM HARDWARE

The system shall consist of one to four synchronous television (CCTV) camera(s) or other synchronous video source(s), an automatic control unit (ACU), a supervisor computer and an RGB video monitor.

1.2 SYSTEM SOFTWARE

The system shall be able to detect vehicles in multiple traffic lanes. A minimum of 48 detection zones shall be user-definable through interactive graphics by placing lines and/or boxes in an image on a video monitor. The user shall be able to redefine previously defined detection zones. The ACU shall calculate traffic parameters in real-time and provide local non-volatile data storage for later downloading and analysis.

2. FUNCTIONAL CAPABILITIES

2.1 REAL-TIME VEHICLE DETECTION

2.1.1 The ACU shall be capable of simultaneously processing information from a minimum of four (4) synchronous CCTV video cameras, video tape players or other video sources.

2.1.2 The system shall be able to detect the presence of vehicles in a minimum of 48 detection zones within the combined field of view of the cameras.

2.1.3 Different detector types shall be selectable via software. Detector types shall include stop-line detectors, presence detectors, directional passage detectors and speed trap detectors. The speed trap detectors shall report vehicle speed and vehicle type based on length. Three length categories shall be user-definable in software.

2.1.4 Once the ACU has been properly set up using the supervisor computer and RGB monitor, it shall be possible to disconnect the supervisor computer and video monitor. The ACU shall then detect vehicles as a stand-alone unit, calculate traffic parameters in real-time, and store traffic parameters in its own non-volatile memory.

2.2 LOCAL DATA STORAGE

2.2.1 The ACU shall count vehicles in real-time and compute the average of traffic parameters over user-defined time intervals (or time slices), as follows:

a. **VOLUME**

Number of vehicles detected during the time interval.

b. **OCCUPANCY**

Lane occupancy measured in percent.

c. **VEHICLE CLASSIFICATION**

Number of automobiles, single unit trucks or tractor trailers, as defined by length.

d. **FLOW RATE**

Vehicles per hour per lane.

e. **HEADWAY**

Average time interval between vehicles.

f. **SPEED**

Average vehicle speed.

2.2.2 The duration of the time intervals (or time slices) shall be user-selectable as 20, 30 seconds or 1, 5, 10, 15, 30 or 60 minutes.

2.2.3 The time-interval data shall be retained in non-volatile EEPROM flash memory within the ACU for later downloading and analysis. The amount of memory shall be 2 MB or 4 MB, as specified. The base memory of 2 MB shall allow the accumulation of 15-minute time-interval traffic data for 48 detection zones data for a minimum of seven days.

2.2.4 Retrieval of data stored in the non-volatile memory of the ACU shall be via a serial communications port. Provision shall be made for downloading of data via a modem and dial-up telephone lines, via private cable or fiberoptic network, or via direct connection to another computer by cable.

2.3 OPERATION WITH SUPERVISOR ON-LINE

2.3.1 Once the detector configuration has been downloaded from the supervisor computer into the ACU, it shall be possible to operate the video detection system either with the supervisor computer disconnected or on-line.

2.3.2 When the supervisor computer is on-line, it shall be possible to view vehicle detections in real-time as they occur on the RGB video monitor.

2.3.3 It shall be possible to automatically save time-interval traffic data on hard disk following completion of each time interval. This traffic data shall include volume, flow rate, lane occupancy, headway, speed, and vehicle classification based on length category. It shall also be possible to save on hard disk the complete time data for each vehicle detection.

The collected traffic and detection data shall be made available in readily-accessible ASCII format. The video detection software of the host computer shall provide file management routines for efficiently filing, retrieving and reporting of the collected traffic data.

- 2.3.4 It shall be possible to display the captured traffic data on the VGA screen of the supervisor computer in both numeric and graphic formats. The data to be displayed shall be selected by pull-down menus and shall be in the form of windows under the Windows 3.1 graphics operating environment.

3.0 VEHICLE DETECTION

3.1 DETECTION ZONE PLACEMENT

The video detection system shall provide flexible detection zone placement anywhere and at any orientation within the combined field of view of the cameras. Preferred presence detector configurations shall be lines placed across lanes of traffic or lines placed in-line with lanes of traffic. A single detector line shall be able to replace multiple conventional detector loops connected in series.

3.2 DETECTION ZONE PROGRAMMING

- 3.2.1 Placement of detection zones shall be by means of a supervisor computer operating in the Windows 3.1 graphics environment, a mouse, and an RGB video monitor. The RGB video monitor shall show images of the detection zones superimposed on the video image of traffic.
- 3.2.2 The detection zones shall be created by using the mouse to draw detection lines on the RGB video monitor. It shall be possible to save detector configurations on disk, to download detector configurations to the ACU, and to retrieve the detector configuration that is currently running in the ACU.
- 3.2.3 It shall be possible to use the mouse to edit previously defined detector configurations so as to fine-tune the detection zone placement. Once a detection configuration has been created, the supervisor computer system shall provide a graphic display of the new configuration both on its own VGA screen and on the RGB monitor that also shows traffic.
- 3.2.4 It shall be possible to individually adjust sensitivity, persistence and shadow compensation for each detection zone in the system.
- 3.2.5 When a vehicle is under a detection zone, the detection zone shall change in color or intensity on the RGB video monitor, thereby verifying proper operation of the detection system.

3.3 OPTIMAL DETECTION

The video detection system shall reliably detect vehicle presence when the camera is mounted 35 feet (11 m) or higher above the roadway, when the camera is adjacent to the desired coverage area, and when the length of the detection area or field of view (FOV) is not greater than ten (10) times the mounting height of the camera. The camera shall not be required to be mounted directly over the roadway. A single camera placed at the proper mounting height and with the proper lens shall be able to monitor eight (8) traffic lanes simultaneously.

3.4 DETECTION PERFORMANCE

Overall performance of the video detection system shall be comparable to inductive loops. Using standard camera optics and in the absence of occlusion, the system shall be able to detect vehicle presence with 98% accuracy under normal conditions (day & night) and 96% accuracy under adverse conditions (fog, rain, snow).

4.0 ACU HARDWARE

4.1 ACU MOUNTING

The ACU shall mount into a 19" EIA equipment rack assembly or be shelf-mountable. Nominal outside dimensions excluding connectors shall be 5-1/2" x 17-1/4" x 10-1/8" or 140 x 438 x 257 mm (H x W x D).

4.2 ACU ENVIRONMENTAL

The ACU shall be designed to operate reliably in the adverse environment found in the typical roadside traffic cabinet. It shall meet the environmental requirements set forth by the NEMA (National Electrical Manufacturers Association) TS1 and TS2 specifications as well as the environmental requirements for Type 170 and Type 179 controllers. Operating temperature shall be from -35 to +74 degrees C at 0% to 95% relative humidity, non-condensing.

4.3 ACU ELECTRICAL

4.3.1 The ACU shall be modular in design and provide processing capability equivalent to the Intel 486SX microprocessor. The bus connections used to interconnect the modules of the ACU shall be gold-plated DIN connectors.

4.3.2 The ACU shall be powered by 95 - 135 VAC, 60 Hz, single phase, and draw less than 2 A, or by 180 - 265 VAC, 50 Hz, single phase and draw less than 1 A. Surge ratings shall be as set forth in the NEMA TS1 and TS2 specifications.

4.3.3 Serial communications to the modem or supervisor computer shall be through an RS-232/RS-422 serial port. This port shall be able to download traffic data stored in non-volatile memory as well as the real-time detection information needed to show detector actuations. A 9 pin "D" subminiature connector on the front of the ACU shall be used

for serial communications.

- 4.3.4 The ACU shall be available with a NEMA TS1 detector interface for 32 or 64 detector outputs. Output levels shall be compatible with the NEMA TS1, NEMA TS2 Type 2, Type 170 and Type 179 standards. Subminiature 37 pin "D" connectors on the front of the ACU shall be used for discrete detector outputs.
- 4.3.5 The ACU shall be available with a NEMA TS2 Type 1 detector interface for 32 or 64 detector outputs, where the detector information is transmitted serially via RS-485. A "D" subminiature connector shall be used for the serial detector output.
- 4.3.6 The ACU shall be available with two or four RS-170 (NTSC) composite video inputs, so that signals from two or four synchronous video cameras or other synchronous video sources can be processed in real-time. BNC connectors on the front of the ACU shall be used for video input.
- 4.3.7 The ACU shall be available with one RS-170 (NTSC) composite video output, which correspond to one of four video inputs, as selected remotely via Supervisor or front panel switch on the ACU. BNC connectors on the front of the ACU shall be used for video output.
- 4.3.8 As an alternative to RS-170 (NTSC) video format, the ACU shall be available with video inputs and outputs in the PAL/CCIR format.

5.0 CAMERA SYSTEM

- 5.1 The video system shall use medium-resolution, color or monochrome CCD cameras as the video source for real-time vehicle detection. Each camera shall provide 380 lines of resolution. It shall have automatic iris and absolute black reference. The limits of gain, iris and sensitivity shall be adjustable to prevent blooming during nighttime hours.
- 5.2 The NTSC version of the camera shall be a Burle Model TC651EA or equivalent. Modifications of the gain, sensitivity and iris limits, as may be required for optimum performance with the video detection system, shall be completed prior to installation. The camera lens shall provide zoom capability from 8 to 48 mm or a fixed focal length as required for the application. The auto-iris capability of the lens shall operate reliably at -30 degrees C.
- 5.3 The camera and lens assembly shall be housed in an environmental enclosure that is waterproof and dust-tight to NEMA-4 specifications. A 20 watt heater shall be attached to the lens of the enclosure to avoid ice and condensation in cold weather. The enclosure shall be light-colored and shall include a sun shield to minimize solar heating. The enclosure shall be a Burle Model TC9393 or equivalent.

- 5.4 A galvanized steel junction with approximate measurements 12" x 10" x 6" (30 x 25 x 15 cm) shall be provided for each pole used for camera mounting. Each junction box shall contain a terminal block, a ground-fault interrupt circuit and tie points for the coax cable.
- 5.5 A video interface panel measuring 12" x 12" (30 x 30 cm) shall be provided for the inside of the traffic cabinet. The panel shall provide a terminal block, a lightning arrester and a ground isolation transformer for each camera.
- 5.6 SUPERVISOR COMPUTER SYSTEM
- 5.7 The minimum supervisor computer system, as needed for detector setup and viewing of vehicle detections, shall consist of a supervisor computer, a video digitizer board, and an RGB sync video monitor.
- 5.8 Three types of supervisor computer shall be offered:
- a. A laptop or portable computer that is carried to the ACU as needed for detector setup and retrieval of data stored in the ACU.
 - b. An environmentally hardened computer that is installed in the traffic cabinet or other site of the ACU, where the computer stores and manages large amounts of traffic data.
 - c. A desktop computer located in a control room or office environment.
- 5.9 Each type of supervisor computer shall be available from the supplier of the video detection system or commercially as an off-the-shelf item. Minimum specifications for the supervisor computer shall be the following:
- PC-compatible
 - 386 processor
 - MS-DOS 3.3, MS-DOS 5.0 or higher
 - Microsoft Windows 3.1
 - One full-size AT-compatible expansion slot
 - VGA monitor
 - Keyboard
 - Mouse
 - 4 MB of RAM
 - 1.44 MB floppy disk drive
 - 60 MB hard disk drive
- 5.10 A video digitizer board shall be installed in the supervisor computer to capture video images. This board shall fit in the full-size AT-compatible expansion slot specified for the supervisor computer and shall be modified by the supplier as needed for operation with the vehicle detection system.

- 5.11 An RGB sync video monitor shall be driven by the RGB sync output of the Matrox digitizer board in the supervisor computer to display scenes of moving traffic with superimposed actuating detection zones. The monitor shall be a Sony Model PVM-1341 for NTSC or a Sony Model PVM-1342Q for PAL or equivalent.
- 5.12 A 2400 or 9600 baud modem shall be offered for the supervisor computer to allow remote detector setup and retrieval of data stored in the ACU.

6.0 INSTALLATION AND TRAINING

- 6.1 The supplier of the video detection system shall supervise the installation and testing of the video and computer equipment. A technically-qualified representative from the supplier shall be on-site for a minimum of one day.
- 6.2 In the event that the supervisor computer is furnished by the contracting agency, such installation and testing shall be done at the time that training is conducted.
- 6.3 Two days of training shall be provided to personnel of the contracting agency in the operation, setup and maintenance of the video detection system. Instruction and materials shall be provided for a maximum of 20 persons and shall be conducted at a location selected by the contracting agency. The contracting agency shall be responsible for any travel, room and board expenses for its own personnel.

7.0 WARRANTY, MAINTENANCE AND SUPPORT

- 7.1 The video detection system shall be warranted by its supplier for a minimum of one (1) year.
- 7.2 Ongoing software support by the supplier shall include updates of the ACU and supervisor software. These updates shall be provided free of charge during the warranty period.
- 7.3 The supplier shall maintain a program for technical support and software updates following expiration of the warranty period. This program shall be made available to the contracting agency in the form of a separate agreement for continuing support.

GLOSSARY

Actuation - The presence of a vehicle or pedestrian as indicated by an input to the controller from a detector.

Added Initial Portion - An increment of green time added to the minimum initial portion in response to vehicle actuations.

All-red - An interval during which all signal indications at an intersection display red indications.

Approach - All lanes of traffic that enter the intersection from the same direction.

Call - A demand for service registered in a controller.

Clearance Interval(s) - The interval(s) from the end of the right-of-way of one phase to the beginning of a conflicting phase.

Controller (or Controller Unit) - The device that determines the signal indications that are to be illuminated at any given time. The controller is usually located in a cabinet near the intersection.

Cycle - A complete serving of all phases that are operating at an intersection beginning at any one phase and returning to that phase. Also refers to the time required for such a serving of phases.

Delay - The time consumed while traffic or a specified component of traffic is impeded in its movement by some element over which it has no control.

Demand - The number of vehicles desiring to use a section of road during a specified time period.

Density - The number of vehicles on a section of roadway per unit of length, usually expressed in vehicles per mile.

Detector - A device that provides an input to the controller to indicate that a vehicle or pedestrian is present.

Detector Memory - The retention of an actuation for future utilization by the controller assembly.

Extensible Portion - Variable-length portion of the green interval following the initial portion.

Extension Limit - The maximum time of the extendible portion for which actuations on any

traffic phase may retain the right-of-way after actuation on an opposing traffic phase.

Force Off - A command that will force the termination of the right-of-way.

Free Flow - Traffic flow that not impeded.

Full Traffic-Actuated Controller Unit - A type of traffic-actuated controller unit in which means are provided for traffic actuation on all approaches to the intersection.

Gap - The interval in time or distance from the back of one vehicle to the front of the following vehicle.

Gap Reduction - A feature allowing the reduction of the "unit extension" or allowed time spacing between successive vehicle actuations on the phase displaying the green in the extendible portion of the interval.

Green Interval - The right-of-way portion of a traffic phase.

Headway - The time, in seconds, between consecutive vehicles measured from the front bumper of one vehicle to the front bumper of the next vehicle as they move past a given point.

Hold - A command that retains the existing right-of-way.

Incident - An event on or near the roadway which blocks or restricts the flow of traffic. Examples are accidents, stalled vehicles, and spilled loads.

Initial Portion - The first timed portion of the green interval for a phase, that is not affected by actuations received during the green interval for that phase.

Interval - Any one of the several divisions of the cycle during which signal indications do not change.

Isolated Controller Unit Operation - The operation of a controller unit at an intersection without master supervision.

Locking - A mode of a controller phase in which a call is retained by the controller even if the vehicle leaves the detector.

Loop - Wire induction loop, the most frequently used detector in Minnesota and the U.S.

Master Controller Unit - A controller unit that supervises a system of local intersection controllers (secondary controllers).

Maximum - A controller time setting at which the phase will be forced to terminate.

Minimum Green - The shortest green time assured to a phase.

Occupancy - The percentage of time that a detector in a lane on a roadway is covered or occupied by a vehicle or vehicles. The occupancy is computed for given lengths of time, e.g. 30 seconds, one minute, five minutes, and expressed as a percentage.

Offset - The relationship in time between a point in the cycle at a particular intersection and an equivalent point in the cycle at another intersection of reference.

Permissive Period - In system operation, a cross street call entered within this period will be served during the green phase.

Phase Omit (Special skip, Force skip) - A command that causes omission of a phase.

Platoon - A number of vehicles moving together at the same speed as a group. Traffic leaving a signalized intersection when the light turns green is a platoon.

Pre-emption - Transfer of normal signed control to a special signal control mode.

Pre-Timed Controller Unit - A controller unit for operating traffic signals in accordance with a predetermined fixed-time cycle.

Queue - A line of vehicles waiting at a traffic signal.

Recurrent Congestion - Congestion occurring at predictable times daily or weekly due to demand exceeding capacity.

Red Clearance Interval - A clearance interval that may follow the yellow change interval during which both the terminating phase and the next right-of-way phase display red.

Semi-Traffic Actuated Controller Unit - A type of traffic-actuated controller unit in which means are provided for traffic actuation on one or more, but not all, approaches to the intersection.

Spacing - The interval, in distance, from head to head of successive vehicles.

Split - A division of the Cycle allocated to each of the various phases (normally expressed in percent).

Traffic Phase - A part of the cycle allocated to any traffic movements receiving the right-of-way or to any combination of traffic movements receiving the right-of-way simultaneously during one or more intervals.

Unit Extension - The timing interval during the extendible portion which is reset by each detector actuation. The green right-of-way of the phase may terminate on expiration of the unit extension time.

