Optimizing Networks of Traffic Signals in Real Time—The SCOOT Method

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Abstract—**This paper describes how the SCOOT Urban Traffic Control system evolved from research by the British Government's Transport and Road Research Laboratory (TRRL) on the TRANSYT method of optimizing networks of fixed time signals. The key principles of the SCOOT on-line traffic model and real-time signal optimizers are explained. The results of surveys are reviewed, applications are summarized, and some new developments are outlined.**

Introduction

WHERE adjacent junctions in a network of urban road are less than a mile apart and are controlled by traffic signals, major benefits can be obtained by installing an urban traffic control (UTC) system to coordinate the operation of the signals. Such systems use a central computer to control the signal sequences and to monitor their operation; the signals and computer are usually connected by voice grade data transmission lines. The method of controlling the signal sequences can have a significant effect on levels of urban congestion, on fuel economy, and on exhaust emissions. This is the main topic of this paper.

UTC Systems

The first UTC systems came into operation in the mid-1960's, and since then their use has been growing rapidly. In 1987, the U.S. and Canada had in operation or under construction over 300 UTC systems controlling 20 000 signals [7]. The largest is in New York with 3000 signaled junctions under central control. In Japan, 34 500 signals out of a total of 122 000 signals are controlled by UTC systems in 74 cities [6]. The largest UTC system in the world is in Tokyo where 5500 signals are controlled centrally. France has about 50 UTC systems in operation; this covers almost all cities with more than 80 000 inhabitants. Similar numbers of systems are in operation in Britain, a few more in Germany, and about 10 in Australia. Many other countries have UTC systems in their major cities and in some smaller towns.

This rapid growth in the use of UTC systems stems from their success in optimizing traffic flow through urban networks. Experience suggests that, depending on the prior method of signal control, traffic flows, and road layout, coordination can reduce delays and stops by between 10 and 40%. Since the cost of delay at an average signaled junction is likely to be a few hundreds of thousands of U.S. dollars each year, it is understandable that many UTC systems have recovered their capital cost well within the first year of operation.

Coordination on Fixed Time Plans

Signals are usually coordinated on a common cycle time so that the platoons of vehicles that leave one signal arrive at the

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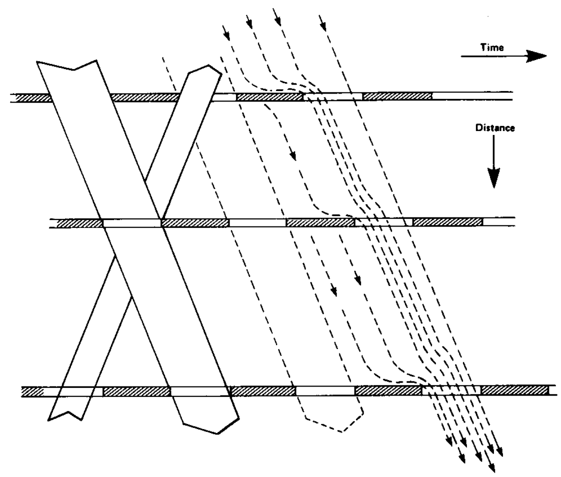

Fig. 1. A time-distance diagram.

adjacent signal just as it turns green. If this can be continued through a series of signals, traffic is able to travel along a "green wave." Fig. 1 shows on a time-distance (T-D) diagram a simple example of green wave "bands" for two directions of travel along an arterial road. Many traffic engineers use T-D diagrams to work out the best way to coordinate signals, and this is one of the most frequent actions taken to optimize control of road networks. Where the green and red times of the signals are held constant for multiple cycles, this is referred to as a fixed time plan. It is usual to prepare at least four different fixed time plans to suit the average traffic flows that are expected in the morning peak, the midday period, the afternoon peak and late evening and nighttime conditions. Special plans may be produced for occasions such as festivals.

On the right-hand side of Fig. 1, typical movements of individual vehicles are shown in time and space—some have to stop and start and so form queues that disrupt the green wave. In such situations, the diagram of a green wave may be misleading. It is a difficult task to estimate average queues using a T-D diagram, particularly in a road network where various routes cross each other. Nowadays such estimates are often made by the use of computer programs, of which probably the most widely known and used is called TRANSYT.

Optimization by TRANSYT

The TRANSYT method [8] was developed originally at Transport and Road Research Laboratory (TRRL); additional features have been added by TRRL and other researchers in Britain [versions up to 9], the U.S. [Versions 6C and 7F], Australia, Sweden, France and other countries. TRANSYT has been shown by surveys in a number of countries to be highly cost-effective—for example, in the Caltrans FETSIM pro-

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gram for fuel economy in California [1]. The TRANSYT method serves as an unofficial international standard against which to measure the efficiency of other methods of coordinating networks of traffic signals. TRANSYT is relevant in the present context because the SCOOT responsive method of control [4] shares some of the same basic concepts, including the optimization criteria.

Optimization Criteria

Bandwidth

There is little point in trying to optimize signal coordination unless the objectives are sensible. Traditionally, traffic engineers have coordinated signals by maximizing the "bandwidth" of the green waves on a T-D diagram; most such diagrams are more complex than that in Fig. 1.

The great merit of the bandwidth criteria is that it is not necessary to know traffic flows in details and T-D diagrams help the traffic engineer to visualize flow patterns. But it is not possible to translate bandwidth measures into financial terms. Further, wherever congestion occurs, the bandwidth concept breaks down because the growth of queues distorts the bands in complex ways. In central urban areas, where many complex traffic movements intersect, "bandwidth" has little meaning.

On lightly or moderately loaded signalized arterials, with few vehicles turning in from side roads, bandwidth optimization usually produces satisfactory results. In more difficult situations there are good reasons for taking the extra trouble needed to minimize queues.

Average Queues

In both TRANSYT and SCOOT, the prime objective is to minimize the sum of the average queues in the area. This criteria is expressed as a performance index (PI), which can be translated from its physical significance of vehicles delayed into financial terms—although there may be arguments about whether to assess the cost of delay, at say, \$5 or \$10 per vehicle-hour.

Action to minimize queues would, in the limit, result in zero queues everywhere, and hence all vehicles that approached a traffic signal should receive a green signal. This ideal condition of multidirectional green waves cannot be achieved in practice, but represents a desirable objective.

Vehicle Stops

The PI in TRANSYT and SCOOT also takes account of the number of times vehicles have to stop. Stops waste energy, irritate drivers, and may cause some accidents, so TRANSYT and SCOOT have a weighting factor that balances the relative importance of queues and stops. Most of the time, signal settings that minimize queues also reduce stops, although there is a tendency to favor rather longer cycle times if a heavy weighting is given to stops. In general, TRRL recommend that one stop should be given a weighting equivalent to 20 s of delay.

Queue Estimation

TRANSYT and SCOOT contain similar "traffic models" that are able to estimate queue size. These models are used by "optimizers" to evaluate alternative signal timings and so help find the "best" settings. The traffic models need to simulate the real world; if not, the optimizers may be misled.

Cyclic Flow Profiles (CFP)

The TRANSYT and SCOOT models are both based on the use of "cyclic flow profiles." A CFP is a measure of the average one-way flow of vehicles past any chosen point on the road during each part of the cycle time of the upstream signal. The average flows in each part of the cycle can be taken over many cycle times (e.g., a 1 h peak as in TRANSYT) or updated every 4 s (as in SCOOT). The cycle time is divided into short time steps which are typically 1-5 s long in TRANSYT but fixed at 4 s in SCOOT. Thus, a CFP records platoons of vehicles as successive steps within the cycle when flows are high. A typical CFP is shown at the top of Fig. 2.

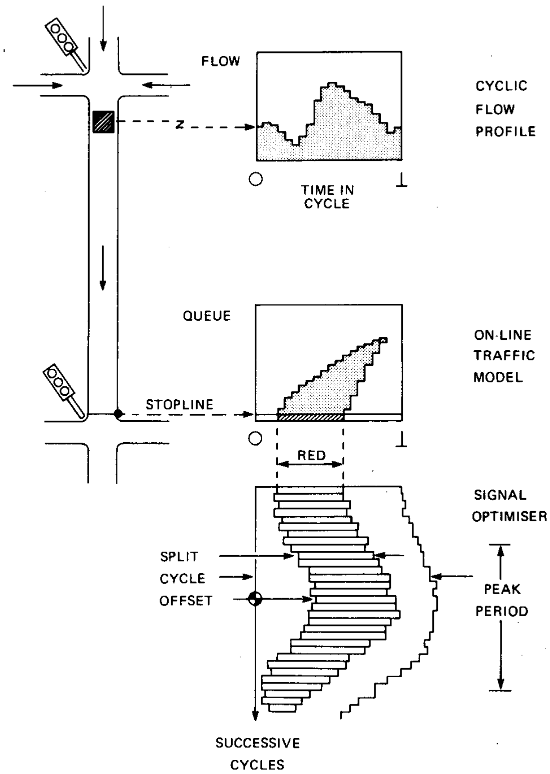

Fig. 2. Key elements of the SCOOT UTC system.

CFP's can be measured quite easily by hand and, at most sites, it will be found that traffic is not concentrated into neat bands (as implied by the bandwidth methods) but is spread out, with varying intensity, over the whole cycle of the signals.

In TRANSYT, the shape of the CFP has to be calculated for each one-way flow along all streets in the area. The calculation is made in an upstream-downstream direction. The accuracy of the calculation depends on the accuracy of the data on average flows, saturation flows, cruise times and so on, that the traffic engineer has to provide as input to the TRANSYT program. It is not difficult to collect these data but it is time-consuming. SCOOT bypasses these processes and achieves accuracy and immediacy by measuring the CFP in real time—but of course, vehicle sensors have to be installed and maintained to provide the data.

Queue Estimation

Once a CFP is known, the computer can be programmed to estimate how many vehicles will reach the downstream signals when they are red—hence both the size of the queue and how long it takes to clear, can be calculated and the effects of alterations in the signal timings predicted. TRANSYT and SCOOT carry out these calculations in a similar manner. Both methods assume that traffic platoons travel at a known cruising speed with some dispersion, and that queues discharge during the green time at a "saturation" flow rate that is known and constant for each signal stopline. The growth and clearance of a typical queue are shown in the middle of Fig. 2. In SCOOT, these estimates are updated every 4 s and constitute the "on-line traffic model" that is used in real time by the signal optimizer.

Traffic Responsive Coordination

In spite of the success of fixed time UTC systems, experience has revealed several limitations that are becoming more important as congestion grows. Fixed time plans are seldom kept up to date, mainly because it takes about 1 man-year of work to produce a set of optimized timing plans for a network of 30–40 signals. Bell [2] estimates that old plans deteriorate to cause an extra 3% of delay a year. Further, even if the plan is up to date, it cannot cope satisfactorily with random variations in flows, for example, after an accident occurs. Finally, no information is available to the traffic manager on the current traffic situation (unless closed circuit television or vehicle detectors are installed). To overcome these limitations, the TRRL cooperated with British Industry (Ferranti, GEC, and Plessey) to develop SCOOT. Research started in the early 1970's.

Principles of SCOOT

The three key principles are:

1) measure CFP's in real time;
2) update an on-line model of queues continuously;
3) incremental optimization of signal settings.

Principles 1 and 2 have been outlined above. The traffic data for the CFP's are collected, usually every second, from inductive-loop sensors located well upstream of signal stoplines, preferably just downstream from the previous junction. In this position, installation costs are reduced and the earliest possible direct prediction is obtained of arrivals at the downstream stopline. Further, the sensor can anticipate "gridlock," which may occur if the queue extends back into the upstream junction. The SCOOT optimizer takes special action when vehicles queue over the sensors.

Incremental Optimization

The third key principle is that the coordination plan should be able to respond to new traffic situations in a series of frequent, but small, increments. This is necessary because research has shown that it is very difficult to predict traffic flows in the next few minutes—hence any "fixed" coordination plan may be out of date before it is calculated or inappropriate after it is implemented (and implementation is likely to cause extra delay during the transition from the old timings to the new).

SCOOT uses an "elastic" coordination plan that can be stretched or shrunk to match the latest situation recorded by the CFP's. This is achieved by optimizing the splits, offsets, and cycle time shown in Fig. 2 in the following way. A few seconds before every phase change, the SCOOT split optimizer calculates whether it is better to advance or retard the scheduled change by up to 4 s, or to leave it unaltered. Then, once a cycle, the offset optimizer assesses whether the PI on streets around each junction can be reduced by altering the offset to be 4 s earlier or later. Favorable split and offset alterations are implemented immediately. In a similar manner, the cycle time of a group of junctions may be incremented up or down by a few seconds every few minutes.

So SCOOT makes a large number of small optimization decisions—typically over 10 000 per hour in a network of 100 junctions. A few decisions may be wrong, but this is unimportant provided the large majority are correct. The effect of these optimization decisions is to vary the signal timings in the manner shown in the lower part of Fig. 2.

TABLE I
REDUCTION IN DELAY FROM THE USE OF SCOOT

Location	Previous Control	Percent Reduction in Delay Time: AM Peak	Off Peak	PM Peak
Glasgow	Fixed-time	−2	14*	10*
Coventry	Fixed-time			
Coleshill Road		23	33*	22*
Spon End		8	0	4
Worcester	Fixed-time	11	7*	20*
	Isolated V-A	32*	15*	23*
Southampton	Isolated V-A	39*	1	48*
London	Fixed-time	(Average 8% less journey time)		

*Results significant at the 95% confidence level.

Surveys of Scoot

The effectiveness of the SCOOT strategy has been assessed by major trials in five cities. The results from the trials are summarized in Table I. The trials in Glasgow and Coventry were conducted by TRRL and those in Worcester, Southhampton, and London by consultants, a university, and the local traffic authority, respectively. In most cases, comparisons were made against a good standard of fixed time coordination usually based on TRANSYT. The table shows that the largest benefits are achieved in comparison with isolated vehicle actuation but, of course, part of this benefit could be achieved by a good fixed time system.

The relative effectiveness of SCOOT varies by area and time of day but overall it is concluded that SCOOT achieved an average saving in delay of about 12% compared with good fixed time plans. Since SCOOT does not "age" in the way typical of fixed time plans, it follows that SCOOT should achieve 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.

Applications

The research on SCOOT was performed in Glasgow, Scotland, with software not suitable for general use. The development of SCOOT for general application was carried out in Coventry, England, using the CORAL high-level real time computer language. It is this version of SCOOT, with subsequent enhancements, that has come into use since the late 1970's in over 40 cities, some eight of which are outside Great Britian. In London, SCOOT controls 250 signals installed in several independent "cells" and is being expanded progressively to replace the older fixed time system, which had about 1200 sets of signals under fixed time computer control.

On the basis of the surveys and subsequent experience, SCOOT is likely to be of most benefit where vehicular flows are heavy, complex and vary unpredictably. Robertson and Hunt [9] describe a simple method of estimating the benefits of coordinating signals by TRANSYT and SCOOT.

Sensor Reliability

The reliability of vehicle sensors is an important aspect of applications. SCOOT is relatively insensitive to sensor failures, mainly because of the incremental nature of the optimizer; default procedures ensure that the performance degrades gradually back to a fixed time plan if successive failures occur and are not rectified. Simulation studies suggest that the benefits of SCOOT are lost if some 15% of sensors are faulty. Experience to date indicates that, with appropriate maintenance procedures, fault rates of well below 5% can be attained without undue difficulty. Up to now, inductive loop sensors have been used, but other types, which give similar information, should be suitable.

New Developments

The preceding sections concentrated on the use of SCOOT to coordinate signals. But SCOOT was conceived for wider purposes, which together may be termed "dynamic traffic management." With growing pressures on road space, such aspects of control are assuming great importance. The TRRL has maintained for the Department of Transport a small research team that has worked with Ferranti, GEC, and Plessey and with universities, consultants, and local government to develop the traffic management capabilities of SCOOT. Proven developments are incorporated in upgraded versions of SCOOT; a list of some such developments follow.

Traffic Information

The information available from SCOOT includes delay, stops, queues, flow, congestion, degree of saturation, spare capacity and traffic signal settings. Information is available on a link or area basis with a 4-s resolution and can be aggregated over any desired time period. Information may be requested by operator or timetable message and output to a line printer. It can also be output to a graph plotter, microcomputer, visual display unit or storage device. A number of graphical displays have been developed which help the traffic engineer to understand the traffic situation in the area under control; these displays are presented in real time on a color VDU. A database system to store and analyze the information [3] has been developed and installed in London where it monitors current traffic levels and builds up historic patterns of traffic conditions. The information is valuable for identification of critical junctions, junction design, the evaluation of traffic management schemes, trends in congestion, etc. Two British universities have data links into operational SCOOT systems and use them for research purposes.

Incident Detection

There is a need to detect automatically serious incidents in urban areas. Research into such technologies is underway at TRRL and within a British university. The aim is to develop and test rapid and reliable methods that can be used, for example, to alert the police to the need for emergency services, initiate broadcasts on local radio stations, and/or automatically take the actions outlined in subsequent sections. The problem is similar to, but more complex than, incident detection on freeways. The pattern of congestion over SCOOT sensors is related in time and space to "typical" patterns, so that unusual situations can be identified and used to trigger corrective actions.

Priority Routes

Weighting and biasing facilities have been provided in the signal optimizers so that traffic engineers can reduce delay on specific links or give preference to progressions along selected routes.

Action at a Distance

The flow of vehicles into a congested area may be reduced by "gating" logic. This logic is triggered when the degree of saturation on critical links exceeds prespecified values. Action is taken to reduce the green times at specified remote stoplines where queues may be stored or vehicles have diversion opportunities. Diversion may be encouraged by variable message signs. Flow out of a congested area may be expedited by similar means. The full value of this powerful facility has yet to be explored.

SCOOT Procedures

Sets of link weightings and flow gatings can be grouped together in "Procedures" to deal with special but recurring events. Currently Procedures are in use in London and are brought in manually by the operator typing one command. Data are being collected which will be used to derive algorithms for bringing in the Procedure automatically, for example when an incident is detected. In the longer term, expert systems may be used to form and initiate procedures.

Congestion Offsets

Another facility allows prespecified offsets to be brought in automatically when queues cover the upstream sensor. If roads become full of stationary vehicles, the best offset is not necessarily the one that minimizes delay on the link. On short links, maximizing throughput may become the overriding consideration to prevent queues blocking back across the upstream junction, which might lead to grid lock.

Calibration of Saturation Occupancy

Earlier versions of SCOOT required the user to set saturation occupancy values (similar to saturation flow) for each signal stopline. The latest version of SCOOT can calculate this value automatically, provided there are downstream detectors in suitable positions. This reduces the time taken to calibrate the system when it is first installed and also allows SCOOT to respond to variations in saturation flow when, for example, a parked vehicle near the stopline reduces the queue discharge rate.

Traffic Signal Status

The latest version of SCOOT monitors the red/green status of the signals and feeds the data into the on-line traffic model—earlier versions assumed that the signals always followed the SCOOT commands. This improves the control of junctions with locally called demand dependent stages. If a demand dependent stage is not called, SCOOT is aware of this and can distribute the green time among the other stages according to the traffic demands. Further, when SCOOT is overridden by an emergency plan, such as for fire engines, SCOOT can model the buildup of any queues and so the optimizer will seek to dissipate the queues once it resumes control.

The European DRIVE Program

The DRIVE program brings together many of the leading researchers in Europe to study how best Information Technology can be used to improve the efficiency and safety of road transport. One-half the cost of about $120 million over three years is met by the European Commission and the other half by participants from some 200 organizations in 14 countries. The TRRL is involved in 12 of the 70 DRIVE projects.

SCOOT is an important element of the TRRL work within DRIVE because it can provide real-time data on congestion levels for input to an in-vehicle route guidance system such as Autoguide [5]. Moreover, if traffic is diverted by AUTOGUIDE to avoid an incident, then SCOOT will adapt the signal timings automatically to the new flow patterns. One DRIVE project is investigating the dynamics of such interactions.

A second example uses research on urban incident detection and congestion monitoring in a DRIVE project on the operation of variable message signs and radio data systems.

Concluding Remarks

Computers were first used to study traffic problems in the 1950's, but it was not until the 1970's that computers came into widespread use for the design and control of traffic facilities. Broadly, the first applications performed traditional tasks in a more efficient manner and are typified by the use of TRANSYT to calculate signal coordination plans. Similarly, computers began to replace special purpose hardware for implementing coordination plans—this process is now well advanced.

In the 1980's, the potential of computers for "intelligent" real time control of traffic began to be exploited. One example of such control is SCOOT—its evolution from TRANSYT is described in this paper.

The 1990's are likely to see the development of computer-based traffic management systems that incorporate in-car driver information and route guidance subsystems in the control loop. Such systems may well make use of on-line traffic models and optimizers of the type built into SCOOT. There are exciting and challenging theoretical and practical problems to be solved before road users benefit from this next generation of traffic management and control systems.

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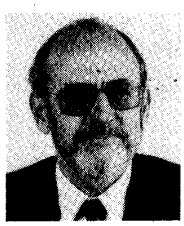

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He worked for nine years on aerospace control systems. His interest in traffic systems began in 1966 when he was seconded from Plessey to Transport and Road Research Laboratory, Crowthorne, U.K., where he conceived, wrote, and tested the TRANSYT program. After work with Plessey and IBM, he joined TRRL in 1972 and started the SCOOT and other projects. He is now Deputy Director, responsible for research by 300 scientists on problems of traffic, safety, and vehicle and highway design.

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He joined the Traffic Engineering Department of Transport and Road Research Laboratory, Crowthorne, U.K., in 1970, and in 1973 became a member of the team working on the research and development of the SCOOT system. He is currently head of the SCOOT/Urban Traffic Control Section and leads an EEC funded DRIVE project on incident detection and traffic monitoring.