ACKNOWLEDGMENT AND DISCLAIMER

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The Sydney Coordinated Adaptive Traffic (SCAT) System Philosophy and Benefits

A. G. SIMS AND K. W. DOBINSON

Abstract—**Sydney, Australia, just as many major cities in the world, has seen traffic movement become more and more congested despite capital expenditure on road construction and widening, on public transport systems, and on traffic management measures. SCAT, the coordinated adaptive traffic signal system, now being installed in Sydney, offers a substantial improvement to movement on arterial roads at low cost thereby enabling usage of the arterial road network to be optimized. An initial trial on a length of arterial road showed advantages in journey time over optimized fixed-time signal coordination of 35–39 percent in peak periods. SCAT is unique in that it consists entirely of computers and is totally adaptive to traffic demand. Its communication network provides extremely powerful yet flexible management of the system. The system, the system philosophy, and the benefits it is expected to yield are described. The benefits are not only in reduced delay, improved flow, and decreased congestion, but also in reduced accidents, lesser usage of petroleum resources, decreased air pollution, and improved residential amenity.**

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THE SYDNEY TRANSPORT SCENE

TRAFFIC on most arterial roads in Sydney, Australia, is at or near capacity on the many radial routes which extend for 30 km from the central business district (CBD). Even a minor disruption, such as a broken-down vehicle, causes a serious disruption to traffic flow, with the resultant congestion affecting many kilometers of the route. This traffic congestion which extends through most of the daylight hours, in addition to its time-consuming delay to people and goods movement, wastes the scarce petroleum resources, increases air pollution, and causes traffic to be diverted to residential streets, reducing residential amenity.

Public transport offers little opportunity for relief as usage in peak periods has been optimized: 78 percent of commuters travel to the CBD by train, bus, or ferry [1]. Due to urban sprawl, there is insufficient movement elsewhere in Sydney to justify a train system, while few oppportunities exist for the expansion of bus services. Because of a

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cutback in funds for urban arterial roads, Sydney cannot look forward to a comprehensive freeway system, as in American cities, to ease the situation in the short term. At the same time, traffic management measures such as clearways, priority roads, bus and transit lanes, median closures, turn bans, and the like, have for the most part been taken up to increase the capacity of existing arteries.

This leaves the intersections en route as the ultimate constraint. SCAT, through the comprehensive coordination of traffic signals, offers a breakthrough of this intersection constraint so that usage of the entire arterial road network may be optimized at all times.

Flow rates, particularly in peak periods, fluctuate over a wide range extending from free flow to congested conditions. At the same time, peaks vary in length and traffic will change routes to adapt to route blockages. Congestion extends beyond peak periods due to capacity reduction from nonrestrictive curbside parking on many arterials. The problem is further exacerbated by the vagaries of weather and the consequent attraction of the beaches, and by major sporting events. Thus a real-time dynamic system of the SCAT type offers the only effective means of overall coordination of the traffic signal network.

THE PHILOSOPHY OF SCAT

The System

SCAT is the signalized urban traffic control (UTC) system now being introduced in Sydney. It is exceptional in that it consists entirely of computers and it is totally adaptive to traffic demand.

SCAT comprises one central supervisory PDP 11/34 minicomputer at the control center, 11 remote regional minicomputers (ten PDP 11/34 and one PDP 11/40), and over 1000 microcomputer traffic signal controllers distributed throughout the 1500 km^2 of the Sydney metropolitan area. The central computer also supervises duplicate PDP 11/40 computers which control the 150 slave traffic signal controllers in the Sydney CBD. The distribution of the regional computers, which is determined by the economics of communication, is shown in Fig. 1. Each regional computer maintains autonomous control of its region.

Communication is via rented telephone lines except for the Sydney CBD which is connected via dedicated cable. The interrelationship of the computers is shown in Fig. 2.

The Intersection Computer

The microcomputer intelligence at the traffic signal site is utilized to process strategic data collected from traffic detectors, make tactical decisions on signal operation, and assess detector malfunction. It also incorporates a software method of cableless link coordination (with 11 plans) through synchronous clocks; this provides a fall-back mode of operation that enhances total system security without the need for dual computer systems.

The Regional Computer

Each regional computer controls up to 200 sets of signals as interactive or noninteractive systems as illustrated in Fig. 3. These computers are the heart of the SCAT system. They implement the real-time operation of the signals by analysis of the detector information preprocessed by the microcomputers.

The software and data base are entirely core-resident for reliability. However, disk units are used for the storage of

- the regional computer program and data for reloading purposes,
- a copy of the data for reloading each microcomputer,
- miscellaneous data collected for off-line analysis purposes.

The Supervisory Computer

The supervisory computer does not automatically influence traffic operation but has the following functions:

- outputs traffic and equipment status for fault rectification,
- stores specified traffic data for short term or permanent record,
- maintains core image of each regional computer and reloads the regional computer if required,
- allows central control to monitor system, subsystem, or intersection, alter control parameters, manually override dynamic functions, or plot time–distance diagrams.

The Communication System

To realize the full potential of the distributed intelligence system based on microcomputers, a compatible communication system was required. The local microcomputers dramatically reduce the time demand on the communication channels and on the regional computer, because they perform all the repetitive high-speed functions. They preprocess data and only require information transfers at decision points which may occur at intervals between 1 and 120 s; this is in sharp contrast to traditional hardware systems where data transfers are required at intervals between 20 and 100 ms.

This ability to transfer preprocessed data from local controllers in digital form and the ability to load local computers with control parameters as digital values from the regional computer required that the communication protocol resemble conventional computer-to-computer technology. This communication system, although using conventional 300-bit/s frequency-shift keying (FSK) hardware, is therefore completely software controlled. A sample of communication codes used is given in Table I.

The system is very flexible, powerful, and expandable, and yields unprecedented monitoring and management possibilities. A system operator can remotely check any local controller in fine detail at the regional site or at the central control; its exact state can be seen, all times and plans can be monitored, and all detector states and demands can be viewed; in fact, any memory location in the local controller can be monitored by a system operator. Data can also be referred back to the regional or central master for logging or mass storage. This monitoring capability makes the local controller

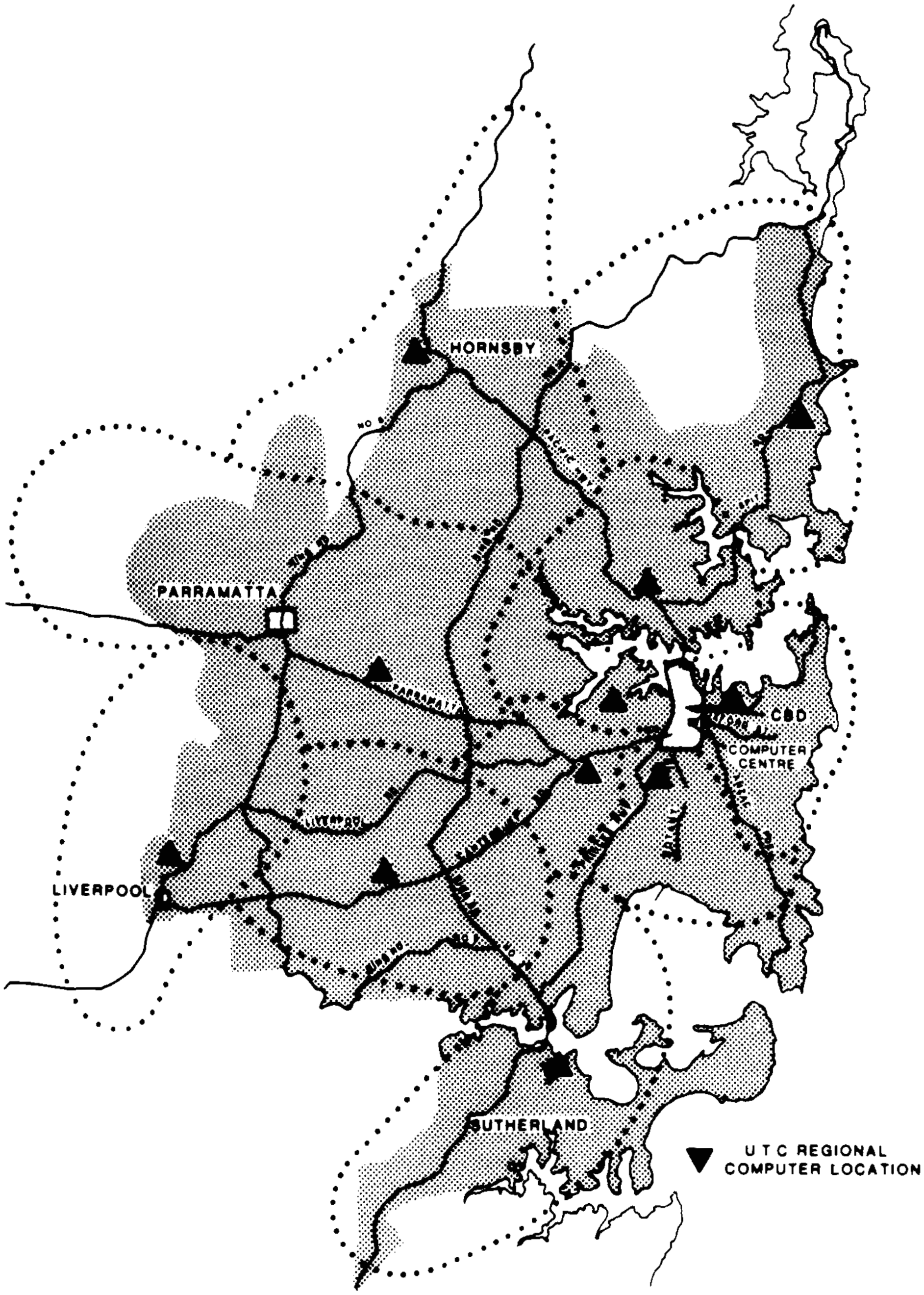

Fig. 1. Sydney regional computer locations.

"transparent" and enables remote fault diagnosis to take place. The system operator also has the capability to change local controller times, fall-back plans, phase sequences, special facilities, and controller operating modes. If desired, the operator can manually remote-operate a controller while continuously monitoring its performance. Selected controller and detector parameters are continuously monitored by the central master and operate alarms when a failure occurs.

Hence the communications system is a major factor in providing a system of high availability that gives extremely powerful management and diagnostic capability. This is apart from traffic benefits due to its contribution to signal coordination. In fact, the SCAT system provides a city-wide street-side data network with distributed intelligence and spare data capacity for subsequent use in public transport priority, vehicle locations, route management, etc.

System Operation

The normal mode of coordination is real-time adjustment of cycle, split, and offset in response to detected variations in demand and capacity. Maximum freedom consistent with good coordination is given to local controllers to act in the traffic-actuated mode. The system is designed to autocalibrate itself on the basis of data received, to minimize the need for manual calibration and adjustment, and to reduce the amount and criticality of preprepared data.

For control purposes, the total system is divided into a large number of comparatively small subsystems varying from

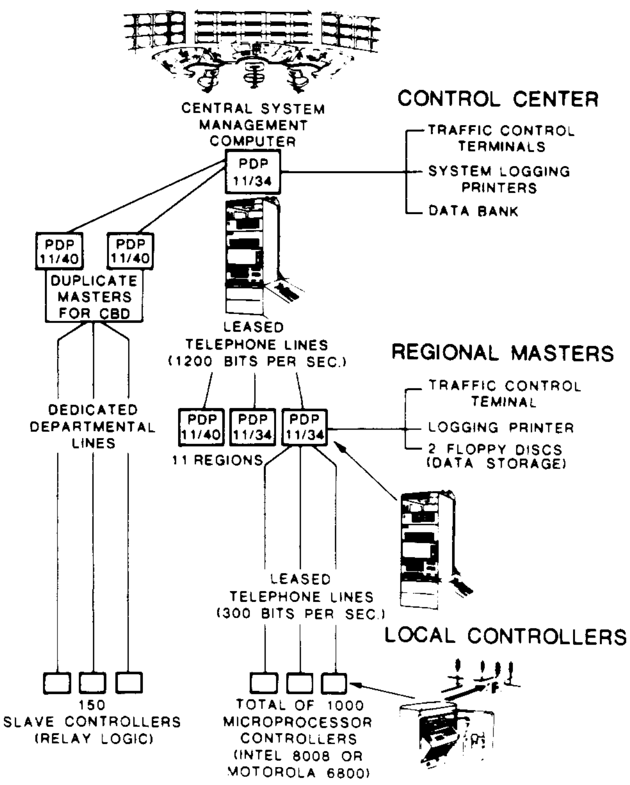

Fig. 2. SCAT computer hierachy.

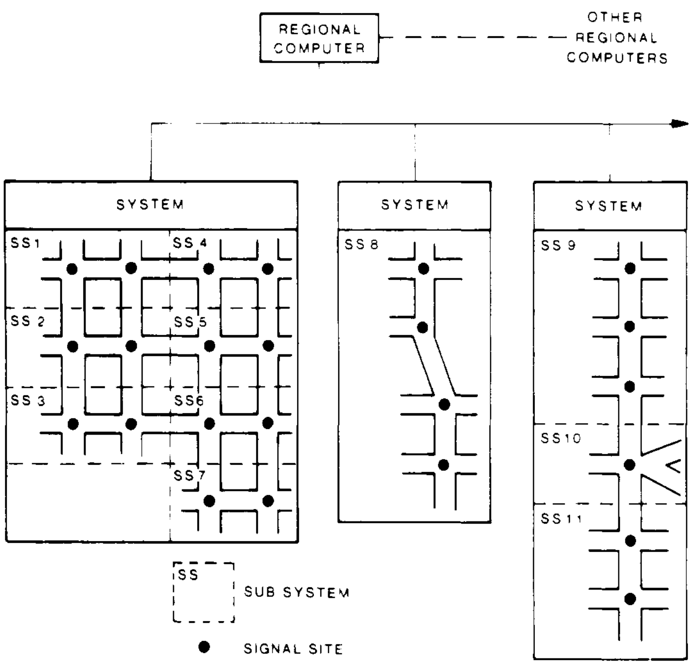

Fig. 3. Regional computer control of systems and subsystems.

TABLE I
SAMPLE OF COMMUNICATION CODES

Mnemonic	Code	No. of Bytes	Message Group	Function
Regional Master to Local Controller Command Codes				
CLPn	02n	1	1	Call Phase n
RST	020	1	2	Request Controller Status
RDM	054	2	2	Request Demand Status
SSF	040	3	3	Set Special Facilities
RSF	041	2	3	Read Special Faciltiies
STS	100	3	4	Store Time Setting in RAM
RTSn	10n	2	4	Read Time Setting in one of several Modes defined by n
SPD	110	3	4	Store Plan Data
RPD	111	2	4	Read Plan Data
SPC	112	3	4	Set Plan Change Schedule
RPC	113	2	4	Read Plan Change Schedule
SCT	004	3	4	Set Clock Time
RCT	005	2	4	Read Clock Time
BVO	044	3	4	Begin Volume and Occupancy Counts
FVO	045	3	4	Finish Volume and Occupancy Counts
RDA	051	2	4	Read Detector Alarms
RMEn	12n	2	4	Read Memory Location in Page n
RMC	116	2	4	Read Memory Checksum
Local Controller to Regional Master Reply Codes				
SST	020	2	2	System Status
CSTn	02n	3	2	Controller Status on Termination Command
DMS	054	2	2	Demand Status
SFS	040	3	3	Special Facilities Set
TBF	100	3	4	Time Setting Buffer Full
TSSn	10n	3	4	Time Setting Set for Mode n
PDS	110	3	4	Plan Data Set
PCS	112	3	4	Plan Change Schedule
CTS	004	3	4	Clock Time Set
VOB	044	3	4	Volume and Occupancy Counts Begun
VOCOn	14n	3	4	Volume and Occupancy of Detector n + 1 for detectors 1-8
VOC1n	15n	3	4	Volume and Occupancy of Detector n + 9 for detectors 9-16
DAS	050	3	4	Detector Alarm Status
MECn	12n	3	4	Memory Contents of Page n
CSM	115	3	4	Checksum of Memory

one to ten intersections (see Fig. 3). This system configuration is in software. As far as possible, the subsystems are chosen to be traffic entities, and for many traffic conditions they will run without relation to each other. As traffic conditions demand, the subsystems "marry" with adjacent subsystems to form a number of larger systems or one large system. This marriage of subsystems is calculated in much the same way as are the interrelationships between intersections within a subsystem. Thus there is a hierarchy of control that is distinct from a hardware hierarchy.

The data for each subsystem specify minimum, maximum, and geometrically optimum cycle length. Four background plans are also stored in the data base for each subsystem. Cycle length and the appropriate plan are selected independently of each other to meet the traffic demand. For this purpose, a number of detectors in the subsystem area are defined as strategic detectors; these are stop-line detectors at key intersections. Various system factors are calculated from the strategic detector data which are used to decide whether the current cycle and plan should remain or be changed.

For linking subsystems together there are four linking plans for each subsystem which define the conditons for marriage with other subsystems, and which use strategic data in much the same way as subsystem plans. When a number of subsystems are linked together, the cycle time becomes that of the linked subsystem with the longest cycle time. The combination of subsystem plans, link plans between subsystems, variable cycle length, and variation of offsets provides an infinite number of operating plans.

Strategic options are available which provide for the operation to be minimum delay, minimum stops, or maximum throughput. These may be either permanent options or can dynamically change at threshold levels of traffic activity.

During normal operation of the system, the regional computer notifies each local controller of a fall-back mode, which can be "lamps off," "flashing," "isolated," or "cableless link" operation. The cableless link operation is the normal fall-back mode as it provides an effective linking system without the

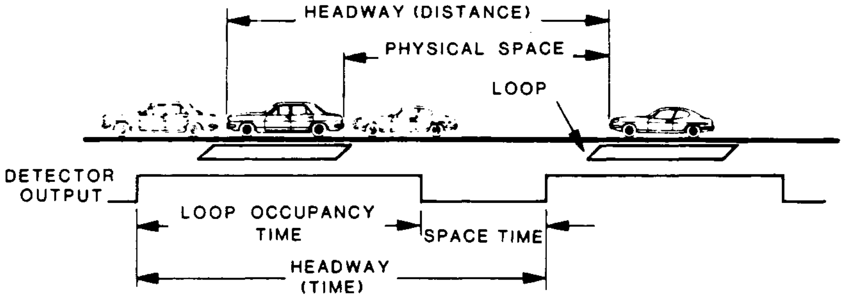

Fig. 4. Relationship between headway, occupancy, and space between vehicles.

need for a master through an in-built software cableless link program.

Traffic Information Processing

In a real-time system it is vital that the detector data used in the algorithms be unambiguous, and that it enable more parameters to be ascertained than is possible from volume and headway. It should also be recognized that the primary cause of delay in a system is the phase split and cycle length of intersections: unless these are first optimized, any benefits from coordination are unattainable.

If demand/capacity is optimized, then coordination provides the means to realize that capacity, as well as reducing delay and stops, by ensuring that platoons will not be fragmented by the asynchronous operation of adjacent signals. The capacity of any traffic lane is not constant, because the ability to flow at saturation varies due to many factors such as weather, time of day, parking, pedestrian friction, downstream conditions, and type of vehicles.

Simple volume and headway information cannot show the difference between these variations and changes in actual demand, and can lead to gross errors in operation. The data from presence detectors can be evaluated to obtain the information essential to describe all the flow parameters, but the detector locations must be in close proximity to the intersection so that high correlation exists between the signal timing and the measurements. In other words, the information will only directly relate to the intersection's capacity if the measurements are made when the traffic should be moving at saturation flow with a green signal. Remote detector locations do not provide this direct correlation, and assumptions on intersection capacities must be made.

In the detector data base the highest flow rate recorded is stored for calibration purposes. As well as the flow rate, the occupancy that occcurred when the flow rate was attained is also recorded. Numerous checks are made to discard erroneous data. This provides the following data relating to maximum flow as reference data:

1) headway (time),
2) loop occupancy time,
3) space time between vehicles,
4) speed.

It is assumed that maximum flow will occur when only cars are present and therefore, as loop length and the length of cars are known, then speed can be calculated approximately. The relationship between these first three parameters is illustrated in Fig. 4.

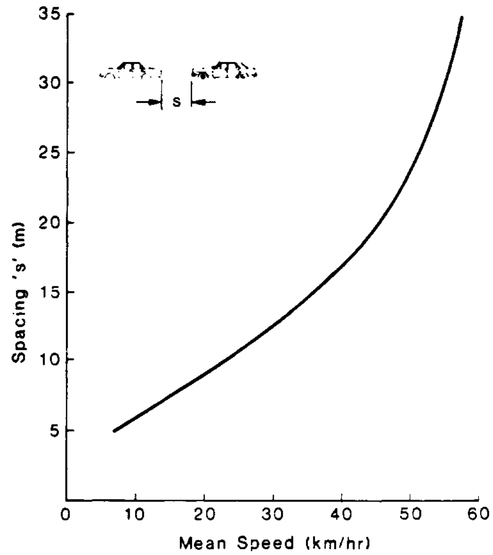

Fig. 5. Speed-spacing relationship [3].

These data are compared against the cyclic data in the various algorithms to determine traffic flow status. The speed/spacing relationship defined by Wardrop [2] and shown in Fig. 5 is used to determine whether speed, and hence saturation flow has varied; i.e., if the actual average space time is less than the reference space time, then speed is less than optimum and flow rate has decreased.

The space time uniquely defines the actual flow conditions as illustrated in Fig. 6. By using the reference speed, the amount of change can be approximated. Neither headway nor occupancy time are appropriate for this purpose because they can vary, as illustrated in Figs. 6 and 7.

Where the flow has decreased due to lower speeds, then, if the decrease is within practical limits, it can be assumed that this is the saturation flow of the lane due to intersection factors. If the decrease is excessive it must be assumed that it is due to downstream conditions.

If the actual average space time is larger than the reference data, this is interpreted as a reduction in demand. For all cycles where flow continues for the whole of a phase in a lane, it is possible to calculate the average vehicle length by means of the measured occupancy, the previously calculated speed, and the reference occupancy. This information would be included in the algorithm for the selection of phase splits and is particularly valuable for including a passive bus priority.

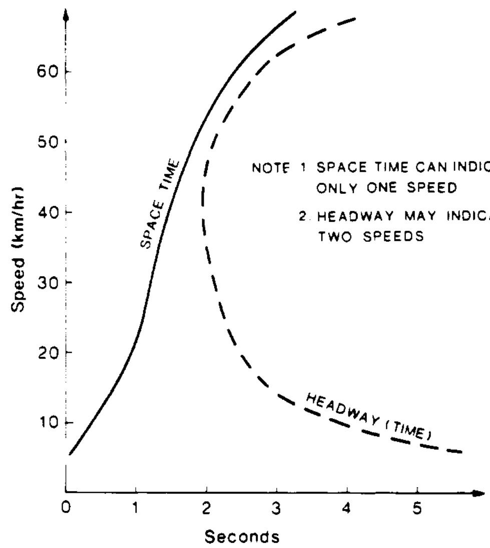

Fig. 6. Space time and headway variation with speed.

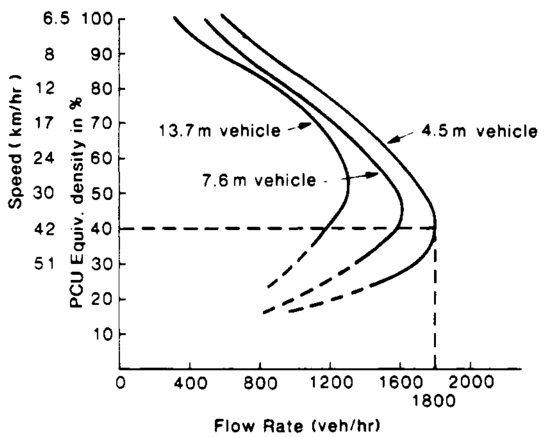

Fig. 7. Variation of vehicle speed and passenger car unit equivalent density with flow rate using 4.5-m long detector zone [4].

THE COST OF SCAT

The total computer configuration enables a system to be developed which incorporates advanced concepts at low cost and which is capable of future amendment without obsolescence. The cableless link fall-back mode saves computer duplication which not only reduces computer costs by 50 percent but avoids the undesirable complexities of dual systems.

Component costs are as follows.

Local controller	\$ 6000 (US\$6600)
Regional computer: cabin, computer, and peripherals	\$ 50 000 (US\$55 000)
Total capital cost for coordination of 1000 sets of signals excluding replacement controllers (this represents about 10 percent of the total signal installation cost)	\$2.8 million (US\$3.1 million)
Annual rental of telephone lines	\$36/km (US\$40/km)
Annual rental of telephone lines for 1000 sets of signals	\$200 000 (US\$220 000).

THE BENEFITS OF SCAT

SCAT offers many community benefits through reduction in travel time, accident reduction, saving in fuel consumption, and reduced air pollution.

Travel Time

Moore [4], in a study of a trial of SCAT in late 1974 on Princes Highway, Newtown, 2.6 km of a Sydney arterial, indicated reductions in travel times compared with optimized fixed-time, using the Greater London Council's (GLC's) combination method of signal coordination, of

- 39.5 percent in the morning peak period,
- 14.5 percent in the main business hours between peaks,
- 32.8 percent in the evening peak period.

Vehicles traversed 8.8×10^9 km in Sydney in 1977, of which 3.1×10^9 km were on arterials that will be covered by SCAT control. Relating the work of Moore to these latter arterials, the estimated savings by SCAT control, compared to the optimized fixed-time coordination of signals, are 40×10^6 km vehicle hours per annum. The latter figure represents an annual savings of \$150 million (US\$165 million), using an average value of \$3.75 (US\$4.12) per hour for driver and vehicle time. (This figure was derived from the \$2.30 per hour in 1973-1974 derived by Bayley and Both [5] and updated to 1979). Translated into motorists' terms, the saving in delay represents 12 min for the average 13-km trip (42 min under optimized fixed-time) in the journey to work on Sydney roads.

Accidents

In 1977-1978, 113 people died and 5800 were injured in a total of 13 225 accidents on arterial roads in Sydney that are planned for SCAT control. Moore and Lowrie [6] showed that signal coordination on arterial roads as compared with isolated operation reduced accidents by 20 percent, with right-angle collisions and pedestrian accidents being the most significant reduction.

Applying the above study to the accident data for 1977-1978, it was estimated that SCAT's accident reduction would save over 1000 injury accidents per annum. Using the average costing of Bayley and Both [5] for accidents, updated to 1979, of \$130 000 (US\$143 000) per fatality, \$5 400 (US\$5900) per injury accident, and \$800 (US\$880) per property damage accident, this represents a community saving of \$8.3 million (US\$9.1 million) per annum.

Fuel Consumption

Moore [4] indicated that 20-48 percent of stops would be saved by signal coordination as compared with isolated operation, with peak periods representing the higher figures. Johnston *et al.* [7] indicated that, for each stop eliminated in travel on an arterial road, 1/40th of a liter of fuel is saved.

By applying these data to the arterial roads to be covered by SCAT, a savings of 37 million liters per annum can be projected, or seven percent of the 525 million liters of fuel used in travel on arterials in Sydney. This is 1.5 percent of the total fuel consumption for the Sydney metropolitan area. At the present retail price this is a savings of $9 million (US$10 million) annually. To the average motorist this means a savings of two liters per week in the journey to work or a saving of $25 (US$27.5) per annum for work journeys.

Air Pollution

The Sydney Area Transportation Study (SATS) [1] indicated that 360 km, or 15 percent, of the developed area of Sydney exceeded the World Health Organization (WHO) eight-hour average goal of 9 ppm of carbon monoxide (CO) in 1971. 90 percent of the CO emission is from motor vehicles. By the installation of SCAT, the improvements in average speed estimated by Moore [4] over optimized fixed-time coordination represents 25 percent overall. This corresponds to an 18 percent decrease in CO emitted by arterial road traffic [8].

Considering emissions from other sources and nonarterial road traffic, the net reduction in CO adjacent to SCAT-controlled arterials is estimated at 13 percent. With the highest emission of CO adjacent to arterials, the expected decrease in the area of Sydney exceeding the WHO level is 60 km^2, i.e., a 16-percent reduction. This represents a seven-percent reduction in CO release in the Sydney metropolitan area as against optimized fixed-time coordination.

Hydrocarbon emissions are not improved to the same degree. Only 65 percent of the hydrocarbons arise from motor vehicles. SATS [1] indicated that 35 percent of the Sydney area exceeded the WHO goal of 0.24 ppm in 1971.

The 25-percent improved speed of travel with SCAT over optimized fixed-time coordination represents a 12-percent decrease in hydrocarbon emissions [8]. It is estimated that this will reduce the total atmospheric concentration of hydrocarbons in the Sydney region by two percent. The greatest benefit will be alongside arterial roads, but overall it will not make a significant reduction in the area above the WHO goal.

The increase in average vehicle speeds from SCAT does not decrease emissions of nitrogen oxides; in fact, the 15-percent expected increase would increase nitrogen oxides emitted by vehicles on arterials by 30 percent [8]. This is estimated to increase the area of Sydney which exceeded the three-hour average goal of 0.1 ppm in 1971 from the six percent determined by SATS to nine percent. This increase is not critical from a health viewpoint, but can be significant in the formation of photochemical smog.

Photochemical smog is a problem in Sydney. Ozone is the measure of photochemical smog, being one of its constituent components together with nitrogen dioxide, peroxyacetyl nitrate, and oxidants. Ozone levels are rising as illustrated in Fig. 8 for the monitoring station at Lidcombe in the western suburbs of Sydney [9].

The effect of SCAT on photochemical smog is complex, as it is derived from combinations of oxides of nitrogen and hydrocarbons which are affected differently. The predicted reduction in hydrocarbons by SCAT will reduce the formation rate. However, the probable attraction of additional traffic to the arterials by the improved flow conditions will increase concentrations of emissions along these routes,

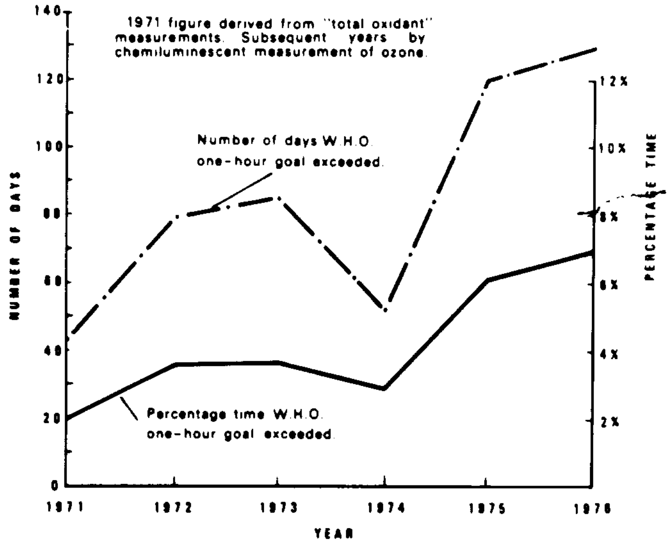

Fig. 8. Ozone concentration, Lidcombe [9].

particularly of nitrogen oxides, causing increased local smog concentrations. The net resultant immediate change in photochemical smog due to SCAT is estimated as minimal. However, as vehicle emission controls reduce hydrocarbon levels, the improved travel speeds will become progressively more effective in reducing oxidant formation and as a consequence the photochemical smog.

Other Benefits

The improved flow on the arterials resulting from SCAT will attract traffic from residential streets which are presently used as bypasses, with a consequent improvement in residential amenity through reduced air pollution, reduced traffic noise, reduced accidents, and reduced physical intrusion by vehicles.

Traffic volume data collection and analysis is being included as an integral part of the SCAT scheme. This replaces automatic and manual collection of these data which are required for road planning and design with substantial cost savings. SCAT offers a greater volume of original data which improve the accuracy level of all data. Storage is in mathematical model form to obviate the need for large computer core storage. SCAT also offers a simple low-cost travel-time data monitoring system for assessing the effects of road proposals. This is to be added to the system.

SCAT OFFERS A FUTURE

SCAT offers a totally adaptive UTC coordinated network signal system of high intelligence at low cost. It offers substantial savings in delay to motorists, principally on arterial roads, and particularly during peak periods. Its peripheral benefits in substantial accident reduction, major savings in fuel consumption, reduced air pollution, and improved residential amenity cannot be overlooked at this time of grave concern in these areas. It offers options for data collection, traffic volume, and travel time data, and for the introduction of variable message signing, reversal flow of lanes, and who knows what else—all at minimal additional cost. SCAT is the UTC signal system for the 1980s.

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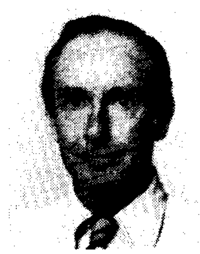

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Hampton Roads Traffic Surveillance and Control System

JOEL SCHESSER, MEMBER, IEEE, AND DONALD N. TANNER

Abstract—**A surveillance and control system was designed and implemented for the Hampton Roads Bridge–Tunnel Crossing connecting Hampton and Norfolk, VA. The facility is a part of the Interstate 64 subsystem and consists of two bridges at each end connected by two two-lane tunnels. This system has been operating successfully since November 15, 1977. The system provides the means for improving vehicular throughput and reducing congestion, improving the management of vehicle incidents and facility operations, improving motorist information, improving environmental conditions, and improving traffic data collection. A control room situated in one of the four tunnel ventilation buildings is the nucleus of the traffic management activities. The system enables vehicle flow control of tunnel access; incident detection, incident verification, and incident operations management; automatic response to environmental and overheight problems; hardware monitoring of the signs, signals, and vehicle detectors; execution of major traffic operations on the faculty upon operator request; and daily reporting and logging of system events. Vehicle data are collected and accumulated by the system and are used for reporting and for performing incident detection and access control.**

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INTRODUCTION

THE Hampton Roads Traffic Surveillance and Control System was designed and developed for the bridge-tunnel facility connecting Interstate Route 64 between Hampton and Norfolk, VA. The system is fully integrated and combines five major components: traffic control, safety surveillance, environmental surveillance, communications, and equipment status. Within the system these components provide for

- maximum vehicular throughput and reducing congestion,
- improving the management of vehicle incidents and facility operations,
- improving motorist safety and information,
- improving environmental conditions, and
- improving traffic data collection.

The system was designed in conjunction with construction of a second tunnel for relieving traffic congestion on the 9.8 km (6.1 m) of eastbound and westbound roadways of Route I-64 between Willoughby Spit in Norfolk and Hampton, VA. As depicted in Fig. 1, the facility consists of dual two-lane tunnels and trestle-type bridges which connect the tunnels to the mainland. The tunnel portals and ventilation fan buildings are

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