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Reference:

AKÇELIK, R., BESLEY M. and CHUNG, E. (1998). An evaluation of SCATS Master Isolated control. *Proceedings of the 19th ARRB Transport Research Conference (Transport 98)* (CD), pp 1-24. ARRB Transport Research Ltd, Vermont South, Australia.

September 2001

An evaluation of SCATS Master Isolated Control

Rahmi Akçelik, Mark Besley, Edward Chung

ABSTRACT

The effectiveness of SCATS Master Isolated (SMI) control for non-coordinated signalised intersections was evaluated using vehicle-by-vehicle simulation including an evaluation of the effects of detector failure, as well as field surveys. Various SCATS-like adaptive control algorithms were developed and tested through extensive simulation tests with a wide range of demand flow patterns and a large number of control parameter combinations. Traditional vehicle-actuated and fixed-time control were also evaluated. The results for Algorithm 9, which was closest to the SMI method, and the traditional vehicle-actuated control method are presented in this paper. A new survey method was developed, trialed and used for the surveys. The survey method produced a large number of timing, capacity and performance statistics. The surveys produced results that are in line with the results of simulation studies.

The overall conclusion is that SMI control gives better intersection performance than traditional VA control as indicated by lower delays and shorter queue lengths achieved with shorter cycle times. The SMI green splits based on the equal degree of saturation principle tend to favour major movements. While this generally results in shorter cycle times and reduced major road queue lengths, slightly higher delays to minor movements may result in some cases. The difference between the performance of the two control methods observed in field surveys was not large. This was probably due to efficient vehicle-actuated control settings used at the intersection surveyed. Evaluation of various detector failure cases indicated substantial benefits from the SCATS Master Isolated control method in terms of all performance measures considered. Longer cycle times, higher degrees of saturation and substantially longer delays (including minor movements) and queue lengths were observed with the traditional VA control.

Acknowledgements

The authors thank Peter Lowrie (Roads and Traffic Authority of New South Wales) and David Nash (Vic Roads) for valuable advice on the work reported in this paper,

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Introduction

This paper presents the results of the first stage of ongoing research on the SCATS Master Isolated control method for isolated (non-coordinated) signalised intersections. The work was conducted under a project initiated by Vic Roads and funded by AUSTROADS. Further research was funded by the Roads and Traffic Authority of New South Wales.

A key element in operating an efficient urban road system is the control of signalised intersections. A significant proportion of existing signalised intersections in Australia are controlled as isolated sites using the traditional vehicle-actuated (**VA**) control (Akçelik 1995a) or SCATS Master Isolated (**SMI**) control (Lowrie 1982, 1990). At the time of the investigation reported in this paper, out of a total of 1758 signal sites, Vic Roads operated 462 sites under traditional VA control and approximately 200 sites under SMI control.

The effectiveness of SCATS Master Isolated control in comparison with the traditional VA control was evaluated in a comprehensive way using detailed vehicle-by vehicle simulation including an evaluation of the effects of detector failure, as well as field surveys at the intersection of Ferntree Gully Road and Scoresby Road in Melbourne.

Various SCATS-like adaptive control algorithms were developed and tested through extensive simulation tests with a wide range of demand flow patterns and a large number of control parameter combinations. The algorithms determined required signal timings on a cycle-by-cycle basis in a way similar to the current SCATS method (Lowrie 1982, 1990). Traditional vehicle-actuated and fixed-time control were also evaluated. Alternative adaptive control methods were evaluated in terms of their basic ability to cope with random variations in individual vehicle headways without a change in the average demand flow rate, and in terms of their ability to cope with changes in the demand flow patterns.

A new survey method was developed, trialed and used for the surveys. The survey method produced a large number of timing, capacity and performance statistics including delay, back of queue, proportion queued, queue clearance time, effective green and red times, saturation flow, capacity, and degree of saturation. The surveys produced results that are in line with the results of simulation studies.

The overall conclusion is that SMI control gives better intersection performance than traditional VA control as indicated by lower delays and shorter queue lengths achieved with shorter cycle times. The difference between the performance of the two control methods observed at the intersection of Ferntree Gully Road and Scoresby Road was not large. This was probably due to efficient vehicle-actuated control settings, i.e. short gap time and maximum green settings, used at this intersection. Evaluation of various detector failure cases indicated substantial benefits from the SCATS Master Isolated control method in terms of all performance measures considered. Longer cycle times, higher degrees of saturation and substantially longer delays and queue lengths were observed with the traditional VA control.

Other recent ARRB TR research on actuated and fixed-time signal timing and performance has produced a substantial body of related information (Akçelik 1994, 1995a-c, 1997; Akçelik and Besley 1996, Akçelik and Chung 1995; Akçelik, Chung and Besley 1997). The results of this research have been incorporated into the SIDRA software package (Akçelik and Besley 1998), and the 1997 edition of the US Highway Capacity Manual (Courage, et al 1996; Transportation Research Board 1997).

SCATS-Like Algorithms

Various adaptive control algorithms which are similar to the current SCATS Master Isolated (SMI) method were developed. The algorithms differ in terms of how the green times and cycle time for the next cycle are determined. Common characteristics of these algorithms are:

- a measure of the degree of saturation is used to determine the demand in the last cycle, which is then used to determine the required green times and cycle time for the next cycle;
- in calculating the required green times, minimum green time constraints apply but maximum green time constraints are not used,
- in calculating the required cycle time, the maximum cycle time constraint applies, and weighting of cycle times over several previous cycles may be applied;
- the required green times are employed as *maximum green times* during the next cycle;
- the actual green times, and therefore the actual cycle time, will differ from the required values according to the actual demand conditions in the next cycle since minimum, gap and waste changes as well as rest periods (extended green periods due to the lack of conflicting demand) are possible as in traditional VA control (see Akçelik 1995a);
- the actual degrees of saturation will differ from the target degrees of saturation for the same reasons as in the previous point;
- the normal actuated control settings apply with the minimum, gap and waste settings as user-specified parameters and the maximum green setting calculated by the algorithm every cycle in response to the measured demand;
- the target degrees of saturation and the maximum cycle time are user-specified control parameters; in the research reported in this paper, the same target degrees of saturation were specified for all movements allowing for the use of equal degree of saturation (EQUISAT) principle in determining the required green times and cycle time;
- presence detection is used.

Nine algorithms were developed during the research reported in this paper. These differed from the actual SMI method to varying degrees. Algorithm 9 was closest to the actual SMI method. This algorithm emulated the SCATS green split algorithm (green times by flow ratio). The cycle time was calculated from a practical cycle time formula that used target (practical) degrees of saturation, and was subject to a maximum cycle time constraint.

Evaluation

Evaluations were based on the following performance measures:

- average intersection delay, i.e. the flow-weighted average delay for all movements (seconds per vehicle),
- largest average movement delay, i.e. the largest average delay for any movement (seconds per vehicle),
- largest average back of queue for the intersection, i.e. largest average back of queue for any movement (vehicles), and
- average cycle time (seconds).

For the cases with unequal conflicting movement demands, the average back of queue for the intersection is the back of queue for the major movement. All performance measures are qualified as better if they have lower values. This applies to cycle time as well when judged on its own right since a lower cycle time offers advantages in terms of short lane, opposed turn and shared lane capacities, reduced chance of downstream queue interference, and reduced pedestrian delays.

Simulation Tests

Simulation tests were carried out for several examples which include multiple flow periods with different traffic demand levels (peak and non-peak demand conditions). Testing of transitions between different demand levels allowed assessment of the response characteristics of each algorithm. Equal and unequal demand flow ratios of conflicting movements were considered.

In all cases, a simple two-phase system with a single movement in each phase was simulated (*Figure 1*). This allowed the testing of concepts involved in the development of the control algorithms. The traditional constant queue discharge model was used with saturation flows, s = 1800 veh/h/lane, and start loss and end gain values, $l_s = l_e = 3$ s for both movements. Therefore, lost times and intergreen times were equal ($l = I + l_s = l_e = I = 5$ s), and the effective and displayed green times and red times were equal (g = G, r = R). The simulated cycle time was determined as the sum of displayed green and intergreen times, $c = \Sigma\ (G + I)$. The intersection lost time was $L = l_1 + l_2 = 10$ s in all cases.

All simulation work was performed using the microscopic simulation model MODELC. Originally a roundabout simulation model (Chung, Young and Akçelik 1992), MODELC was modified to generate data required for the calibration of the performance models for fixed-time and vehicle-actuated signals (Akcelik and Chung 1995). Given an average arrival flow rate specified as input, MODELC can generate individual vehicle arrivals with headways that follow various arrival headway distributions. For the work reported here, the bunched exponential model of arrival headways was used with proportion unbunched predicted by an exponential model (Akçelik and Chung 1994).

For each test case, five simulation runs were carried out, and the average value of each statistic was calculated and used as the *simulated* value. For each simulation run, a 15-minute warm-up time was used before the specified flow periods were simulated. The simulated average flow rates differed from the specified input values due to random variations in arrival headways.

Stop-line presence detection was used with effective detection zone length = 4.5 m and detector set-back distance = 1.0 m. Traffic streams consisted of cars only. All cars were of the same length (4.0 m) with spacing per car in queue = 6.0 m. The approach speed was chosen to be 61 km/h. This speed applied to all vehicles during both the saturated and unsaturated flow conditions. The average occupancy time corresponding to these parameter values was 0.5 s. Although the assumption about vehicle speeds during departures from the queue was not realistic, it is of little consequence in terms of the results reported here since all controller settings (gap and waste settings) were specified as headway values. Simulation time unit was 0.1 s which is equal to the time increment used in Australian controllers.

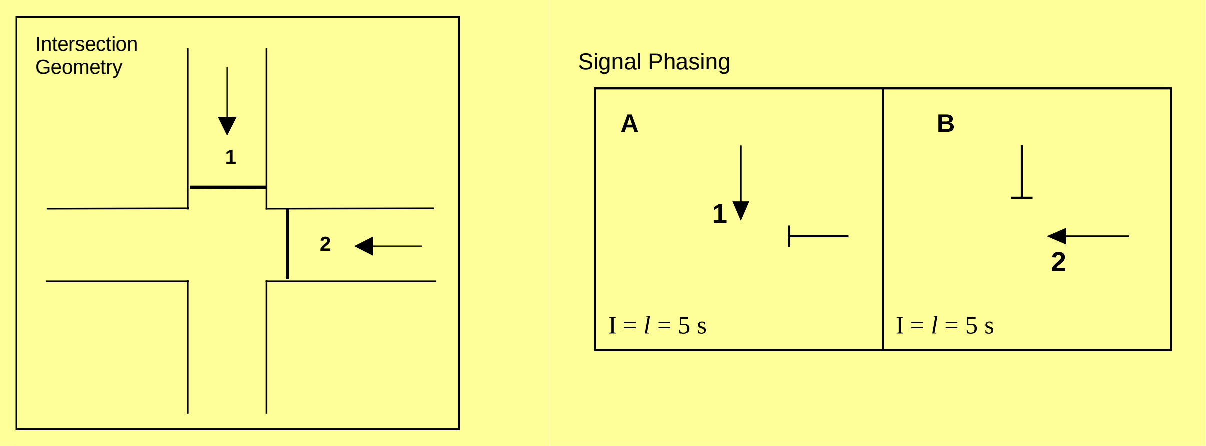

Figure 1 - Simple two-phase system used for simulation tests

The following method is used in simulating ***detector loop failure*** in one lane of a two-lane approach:

(i) In traditional VA control, the detector stays in the *on-state* permanently (i.e. permanent demand). Therefore, the phase is called every cycle (no phase skipping under low flow conditions). It is terminated by *maximum change* only, i.e. it will always extend to the maximum green setting.

(ii) In the case of SCATS-like adaptive control, the detector stays in the *on-state* permanently (i.e. permanent demand) and the consequences are the same as VA control. However, a different maximum green setting applies every cycle based on the calculation of the green times using the information of traffic demand (represented by the flow ratio in the last cycle) from the adjacent lane. This returns demand information which adequately represents the conditions of both approach lanes (assuming equal lane utilisation).

Simulation Results

Simulation results are extensive due to the large number of SCATS-like algorithms tested using a wide range of demand flow and control parameter combinations. In this paper, only a selected summary of simulation results are presented for Algorithm 9 and traditional VA control. Results for Examples 1 to 5 are given, based on the use of the same signal control parameters in all examples. Example numbers are as used in the original research reports. The demand flow pattern for Examples 1 and 2 is shown in *Figure 2*, the pattern for Example 3 is shown in *Figure 3*, and the pattern for Examples 4 and 5 is shown in *Figure 4*. In Examples 1 to 3, Movements 1 and 2 are single-lane movements (s = 1800 veh/h). In Examples 4 and 5, two-lane movements with equal lane utilisation are considered (s = 3600 veh/h).

Examples 1 and 2 differ in terms of the proportion of demand flow rates for Movements 1 and 2 (approximately 1/3 and 1/1, respectively). In Examples 3 to 5, the demand flow rates for the two movements vary in different ways.

In Examples 1 and 2, ratios of the two approach flows remain constant while the demand flow levels change during different flow intervals. As seen in *Figure 2*, the Peak Flow Factor (PFF) is 0.90, the total flow period is T = 60 min, and the peak demand period duration is T_p = 30 min. Arrival (demand) flow rates for the peak half hour, non-peak half hour and the total hour (q_p, q_n, q_a) are shown in *Table 1*.

In Example 3, eight flow intervals of 15-min duration are considered as seen in *Figure 3*. Movement demand flow ratios are seen to reverse between the two peak demand periods (emulating am and pm peak conditions) with equal flow ratios during low flow periods and between the two peak periods. Average flow rate during the total flow period (T = 2h) is 583 veh/h for both movements.

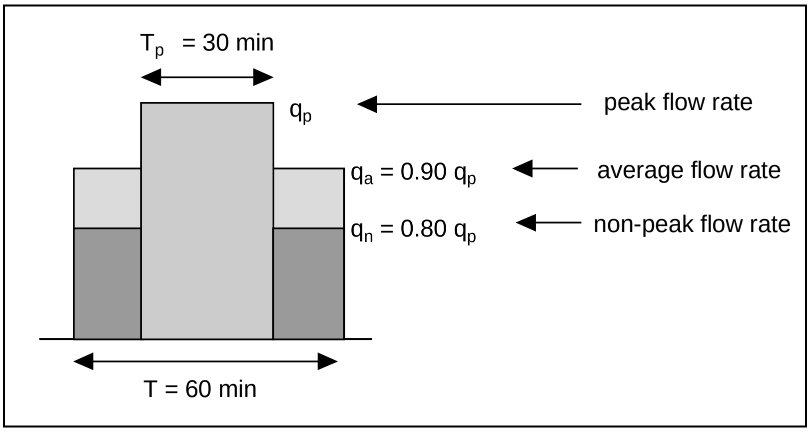

Figure 2 – Variable demand flow pattern for Examples 1 and 2 (same pattern applies for both Movement 1 and Movement 2)

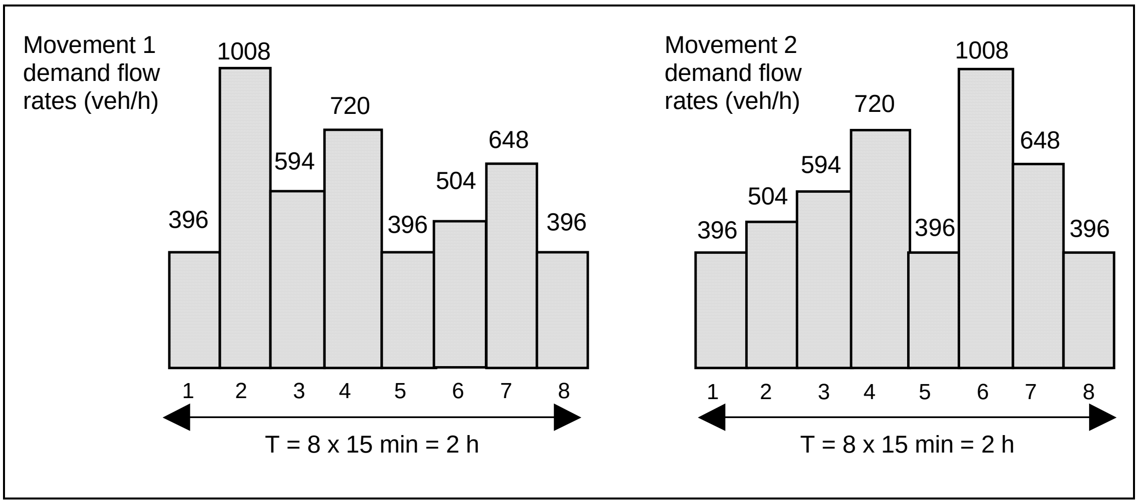

Figure 3 – Variable demand flow pattern for Example 3

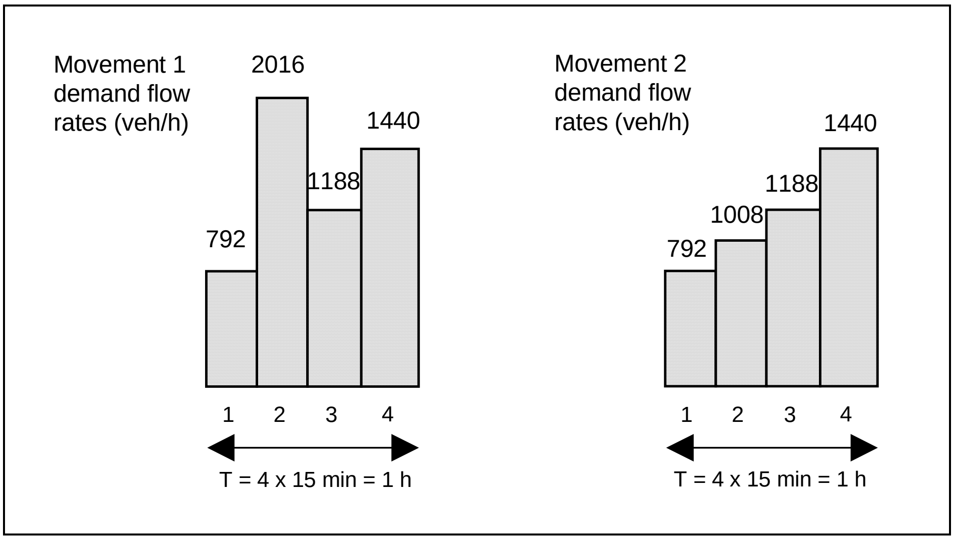

Figure 4 – Variable demand flow pattern for Examples 4 and 5

Table 1

Demand flow rates (veh/h) for Examples 1 and 2

	Peak 1/2 Hour (q_p)		Non-peak 1/2 Hour (q_n)		Average Hour (q_a)	
Example	Mov. 1	Mov. 2	Mov. 1	Mov. 2	Mov. 1	Mov. 2
1	380	1060	304	848	342	954
2	720	720	576	576	648	648

In Examples 4 and 5, four flow intervals of 15-min duration are considered as seen in *Figure 4*. Demand flow rates for Movements 1 and 2 are equal except in Flow Period 2. Average flow rates during the total flow period (T = 1 h) are 1359 veh/h for Movement 1 and 1107 veh/h for Movement 2. Example 5 is same as Example 4 except for *detector failure* on one of Movement 2 lanes.

Results for Examples 1 to 5 were derived using the following settings for all phases (movements):

VA control : G_{min} = 8 s, G_{max} = 70 s
Algorithm 9 : G_{min} = 8 s, c_{max} = 150 s, x_p = 0.70

where G_{min} = minimum green setting, G_{max} = maximum green setting, c_{max} = maximum cycle time, and x_p = target degree of saturation.

In all these examples, gap setting as a headway value was 3.5 s, and headway time setting was 2.3 s (compare with saturation headway of 2.0 s). For Examples 1 to 3, the waste time setting was 7.0 s (= 0.1 G_{max}) for both control methods. For Examples 4 and 5, a large value of waste time setting was used (20 s) so that signal control logic used gap-control only. Headway time and waste settings are used in Australian actuated-signal control method as a type of volume-density control method. These settings were found not to have a significant effect on the results.

Figures 5 to 8 present the comparisons of SCATS-like Algorithm 9 and traditional VA results. Overall, Algorithm 9 is found to give more satisfactory results than the traditional vehicle-actuated control. In particular, the tendency to produce shorter cycle times and reduce major road queue lengths and delays is noted.

The simulation results for detector failure cases (Example 5) indicated substantial benefits from the SCATS Master Isolated control method in terms of all performance measures considered. Longer cycle times, higher degrees of saturation and substantially longer delays and queue lengths were observed with the traditional VA control.

Generally, simulation results indicated that Algorithm 9 gave as good or better results than the traditional VA control with appropriate choice of control settings for both control methods. Algorithm 9 did so with a shorter cycle time. The SMI green split method based on the equal degree of saturation principle tend to favour major movements. While this generally results in shorter cycle times and reduced major road queue lengths, slightly higher delays to minor movements may result in some cases (see *Figures 6 and 7*).

In complicated real-life intersection situations, shorter cycle time means substantial benefits in terms of increased opposed turn, short lane and shared lane capacities, and reduced chance of downstream queue interference. These benefits would mean additional performance gains. Lower cycle times are also preferred in terms of pedestrian delays. For these reasons, Algorithm 9 was considered to offer better overall performance than traditional VA control.

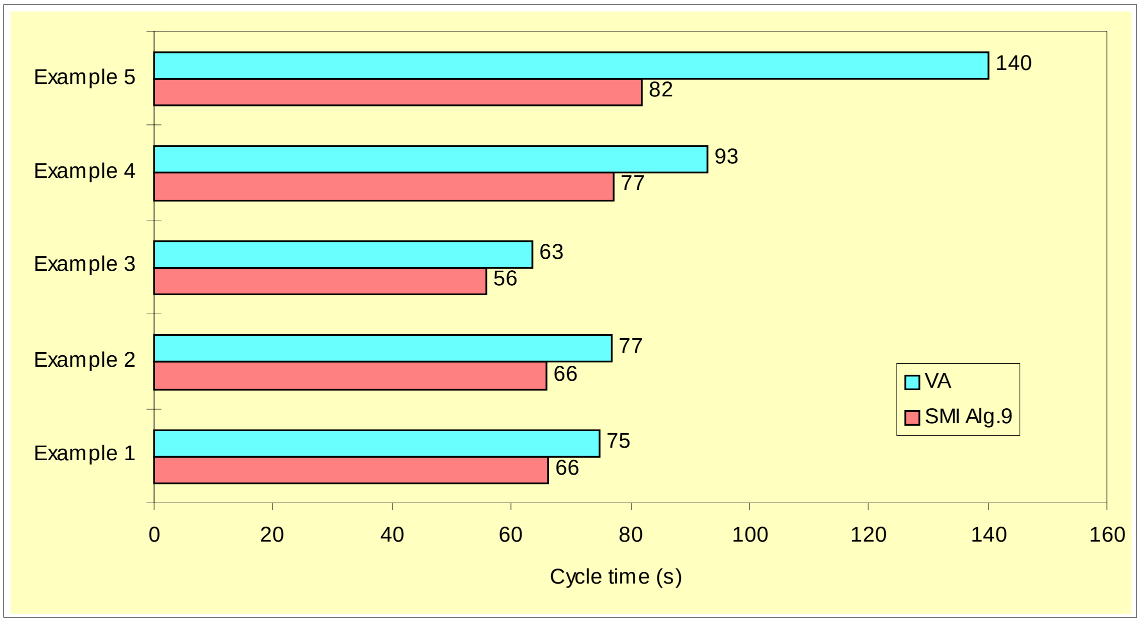

Figure 5 - Comparison of* cycle times *under the traditional vehicle-actuated control and a SCATS-like algorithm (Algorithm 9) in various simulation test cases

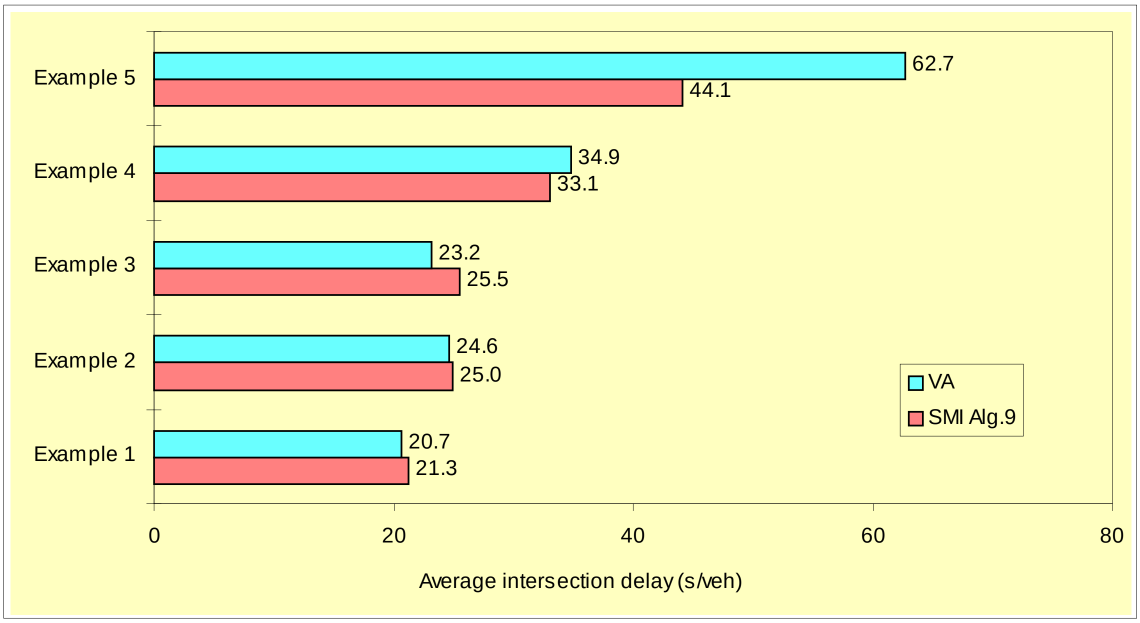

Figure 6 - Comparison of* average intersection delays *under the traditional vehicle-actuated control and a SCATS-like algorithm (Algorithm 9) in various simulation test cases

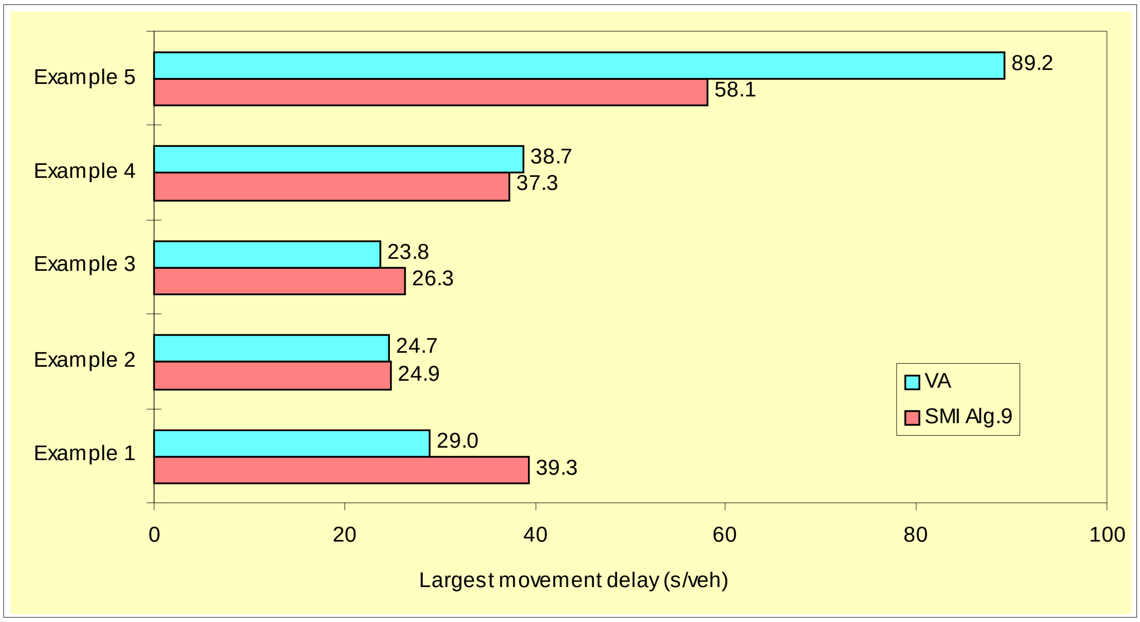

Figure 7 - Comparison of **largest movement delays** *under the traditional vehicle-actuated control and a SCATS-like algorithm (Algorithm 9) in various simulation test cases*

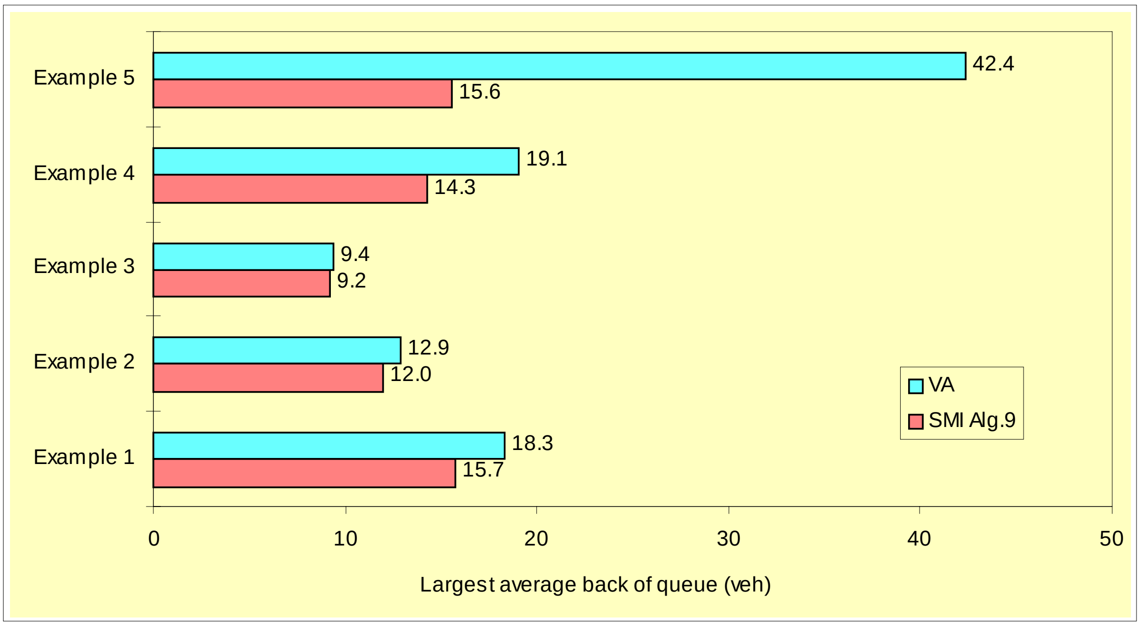

Figure 8 - Comparison of **largest average back of queue** *values under the traditional vehicle-actuated control and a SCATS-like algorithm (Algorithm 9) in various simulation test cases*

Intersection Surveys

Field surveys to evaluate the performance of SMI and VA control methods were planned to satisfy the following requirements:

(i) comprehensive surveys of intersection timings, volumes, capacity and performance statistics;

(ii) surveys during morning and evening peak periods to cover any directional flow effects;

(iii) to be limited to an undersaturated site;

(iv) an isolated intersection with no downstream queue effects;

(v) surveys to be limited to critical lanes in order to minimise cost.

On this basis, the intersection of Ferntree Gully Road and Scoresby Road in Melbourne (Vic Roads Intersection No. 459) was selected. This is a T-junction operating under a three-phase signal system with fully-controlled right turns. The control method is normally SCATS Master Isolated. Intersection geometry with lane numbers based on SCATS detector numbers is shown in *Figure 9*. Lane 7 is a special U-turn lane with very light traffic.

In *Figure 9*, the critical lanes which are surveyed are indicated by an asterisk. The critical lanes were determined using SCATS data and carrying out SIDRA analysis prior to the surveys. Survey results confirmed the critical lane analysis (measured volumes were roughly the same as those used for the initial critical movement analysis).

Signal phasing is shown in *Figure 10*. In the morning peak, Lane 1 (Phases C+A) and Lane 8 (Phase B) are critical, and Lanes 3 and 6 (Phases C and A) operate as non-critical lanes overlapping with Lane 1. In the afternoon peak, Lane 3 (Phase C), Lane 6 (Phase A) and Lane 8 (Phase B) are critical, and Lane 1 operates as a non-critical lane. Signal controller parameters are given in *Table 2*.

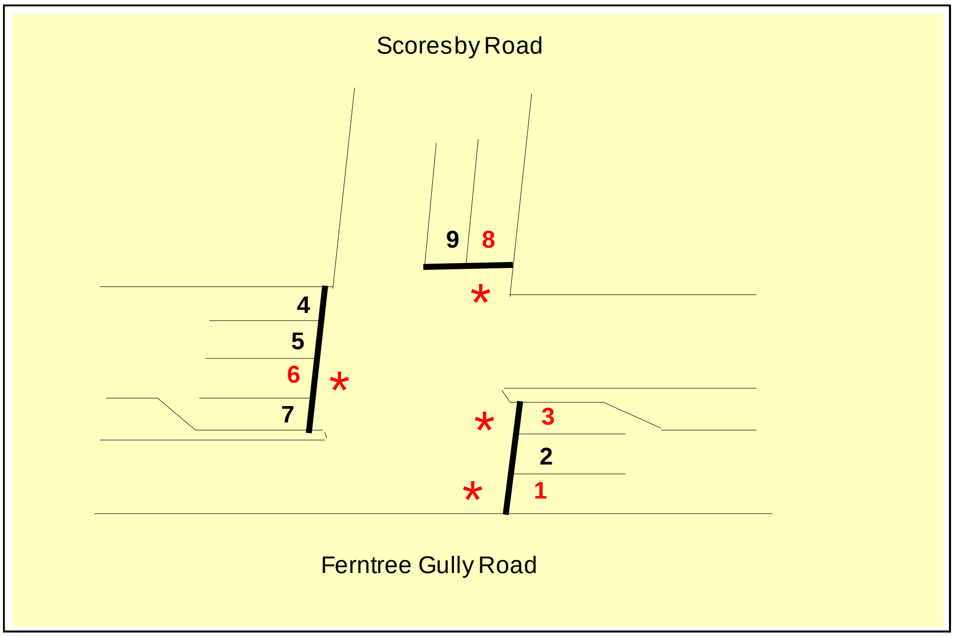

Figure 9 - Ferntree Gully Road - Scoresby Road intersection lane numbers (based on SCATS detector numbers)

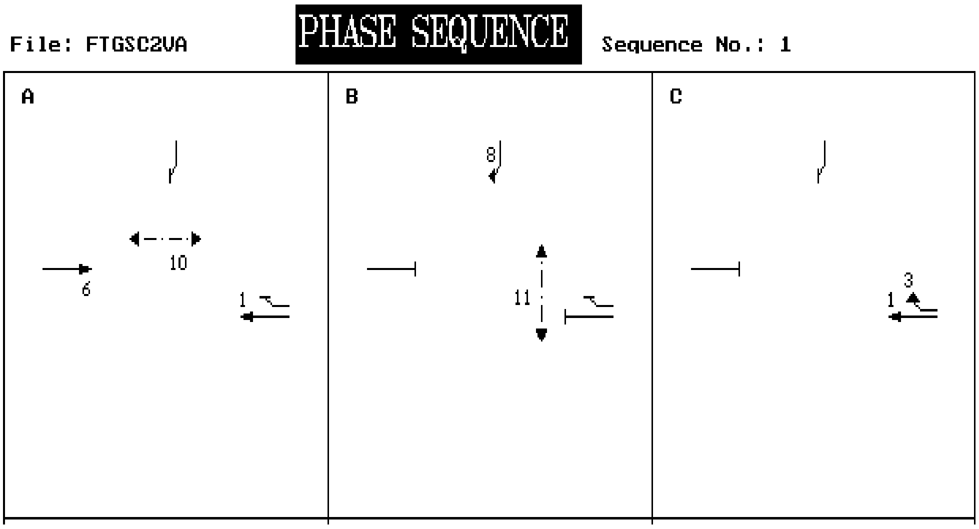

Figure 10 - Ferntree Gully Road - Scoresby Road intersection signal phasing

Table 2

Signal control parameters for Ferntree Gully Road - Scoresby Road intersection (all time settings in seconds)

Phase:	**A**	**B**	**C**
Yellow	4.5	4.0	**3.0**
All red	1.5	2.0	**2.0**
Intergreen	*6.0*	*6.0*	***5.0***
Minimum green	10	8	**6**
Maximum extension green	35	22	**10**
Maximum green	*45*	*30*	***16***
Gap setting	2.5	2.5	**2.5**
Headway setting	0.6	0.6	**1.2**
Waste setting	7.0	7.0	**7.0**
Pedestrian movement number	10	11	
Walk	13	14	
Clearance	6	9	

Maximum cycle time for SCATS Master Isolated Control: 100 s

A new survey method was developed, trialed and used for the surveys. The survey method produced a large number of timing, capacity and performance statistics including delay, back of queue, proportion queued, queue clearance time, effective green and red times, saturation flow, capacity, and degree of saturation. The new survey method was used to collect data for traffic using Lanes 1, 3, 6 and 8 with two observers per lane conducting manual surveys. SCATS data were collected by VicRoads simultaneously with the on-street surveys. The survey dates were Thursday, 18 July 1996 with SCATS Master Isolated operation, and Tuesday, 23 July 1996 with traditional vehicle-actuated signal operation. The survey times on each day were Morning peak period: 7.30 to 9.00 am, and Afternoon peak period: 4.30 to 6.00 pm.

The average flow rates and the phase time ratios (green plus intergreen) from the manual surveys and from SCATS data showed very good agreement. The summary of survey results for 90-min peak periods (7.30 to 9.00 am and 4.30 to 6.00 pm) are given in *Tables 3 and 4.*

As seen in *Tables 3 and 4* and *Figure 11*, the SMI control produces shorter cycle times consistently. This is in agreement with the simulation results for SCATS-like algorithms. Note that, in *Tables 3 and 4*, cycle time values measured for individual lanes differ by a small amount. This is due to various factors related to the survey method such as slightly different starting times and deletion of cycles with bad data which differ from lane to lane.

Comparison of average delays for individual lanes during the 90-min peak periods are shown in *Figure 12*. For this purpose, average delays from the SMI and VA control methods are plotted as a function of the measured average demand flow rates. The trend line shown in these graphs indicate that the SMI method gives lower delays overall considering the 90-min peak periods. The difference between the two methods was negligible considering the 45-min peak periods.

Comparison of the average back of queue values for individual lanes for the 90-min peak periods are shown in *Figure 13*. Trend lines shown in these graphs indicate that the SMI method gives lower queue lengths although the difference between the two methods is small considering the 45-min peak periods.

Table 3

Survey results for the morning peak 90-min period (7.30 - 9.00 am)

	SCATS Master Isolated				Traditional Vehicle-Actuated			
Lane:	**1**	**3**	**6**	**8**	**1**	**3**	**6**	**8**
Cycle time, c (s)	76.7	77.9	76.4	78.3	80.8	83.2	84.1	81.2
Displayed red time, R (s)	30.8	61.3	45.6	52.2	31.6	67.6	50.3	53.8
Displayed green time, G (s)	41.4	13.6	26.3	22.1	44.7	12.6	29.3	23.5
Arv. flow rate, q_a (veh/h)	839	245	313	486	883	230	299	450
Saturation flow, s (veh/h)	1903	2160	1737	1906	1902	2000	1800	2070
End gain, l_e (s)	2.8	2.5	3.1	2.8	2.8	2.7	3.0	2.6
Effective green time, g (s)	44.3	16.1	29.4	24.9	47.5	15.3	32.3	26.1
Eff. Green time ratio, g/c	0.577	0.207	0.385	0.318	0.588	0.184	0.384	0.321
Capacity, Q (veh/h)	1099	447	669	607	1119	368	691	664
Deg. of saturation, x	0.764	0.549	0.468	0.801	0.789	0.626	0.433	0.677
Que. clearance time, G_s (s)	26.5	9.4	10.9	18.5	27.8	10.1	10.1	16.5
Proportion queued, p_q	0.76	0.90	0.77	0.93	0.72	0.96	0.71	0.88
Aver. back of queue, N_b (veh)	13.7	4.8	5.1	10.8	14.5	5.3	5.0	9.3
Aver. delay per vehicle, d (s)	13.2	31.1	18.5	34.2	12.8	41.3	18.2	30.5

Saturation flow is based on zero start loss definition, l_s = 0 s.

Table 4

Survey results for the afternoon peak 90-min period (4.30 - 6.00 pm)

	SCATS Master Isolated				Traditional Vehicle-Actuated			
Lane:	**1**	**3**	**6**	**8**	**1**	**3**	**6**	**8**
Cycle time, c (s)	70.3	71.2	70.6	71.4	84.6	82.5	83.4	84.9
Displayed red time, R (s)	23.3	59.5	35.1	52.0	27.2	67.6	41.7	61.4
Displayed green time, G (s)	42.5	8.7	30.9	15.3	52.9	11.9	37.2	19.5
Arv. flow rate, q_a(veh/h)	478	176	818	335	457	186	779	304
Saturation flow, s (veh/h)	1787	1852	2142	2288	1861	1841	1932	2116
End gain, l_e (s)	3.0	2.9	2.5	2.4	2.9	2.9	2.8	2.6
Effective green time, g (s)	45.5	11.6	33.5	17.7	55.8	14.8	40.0	22.1
Eff. Green time ratio, g/c	0.648	0.163	0.474	0.248	0.660	0.180	0.479	0.260
Capacity, Q (veh/h)	1157	302	1015	567	1228	331	926	550
Deg. of saturation, x	0.413	0.584	0.806	0.590	0.372	0.562	0.841	0.552
Que. clearance time, G_s (s)	11.0	6.8	23.6	13.6	12.2	8.4	30.3	11.7
Proportion queued, p_q	0.53	0.96	0.84	0.94	0.52	0.95	0.90	0.81
Aver. back of queue, N_b (veh)	5.0	3.6	13.5	6.6	5.6	4.1	16.2	5.8
Aver. delay per vehicle, d (s)	6.4	34.5	17.0	27.1	6.9	33.3	24.1	27.9

Saturation flow is based on zero start loss definition, l_s = 0 s.

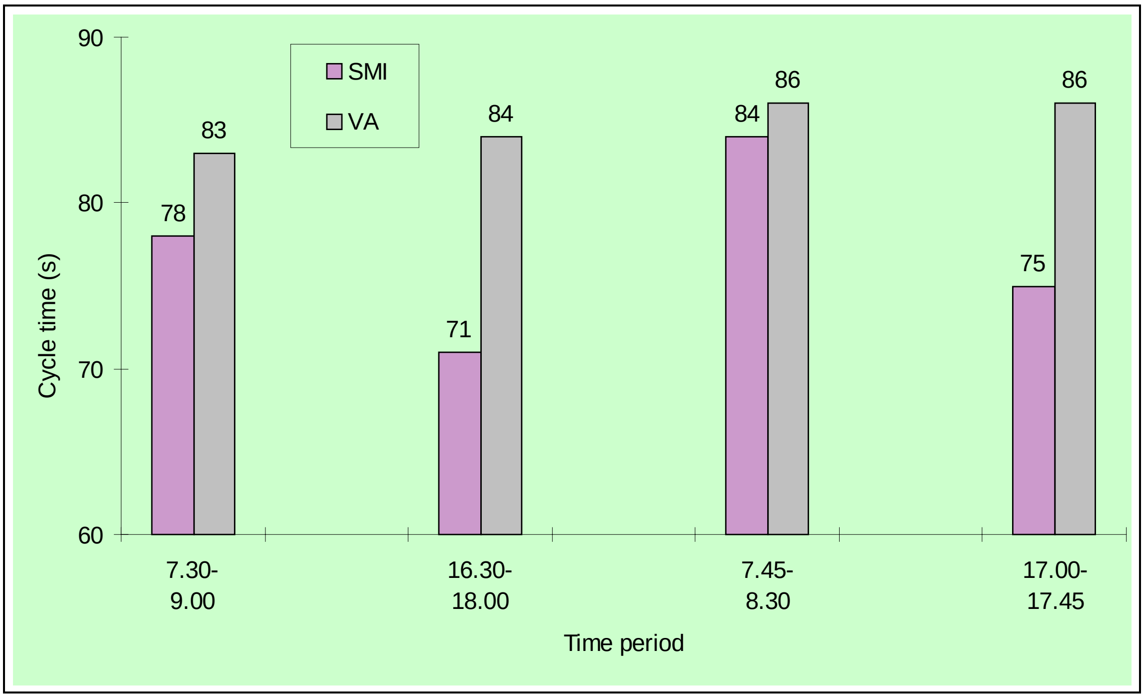

Figure 11 - Comparison of* cycle times *obtained from SCATS Master Isolated and traditional vehicle-actuated control methods

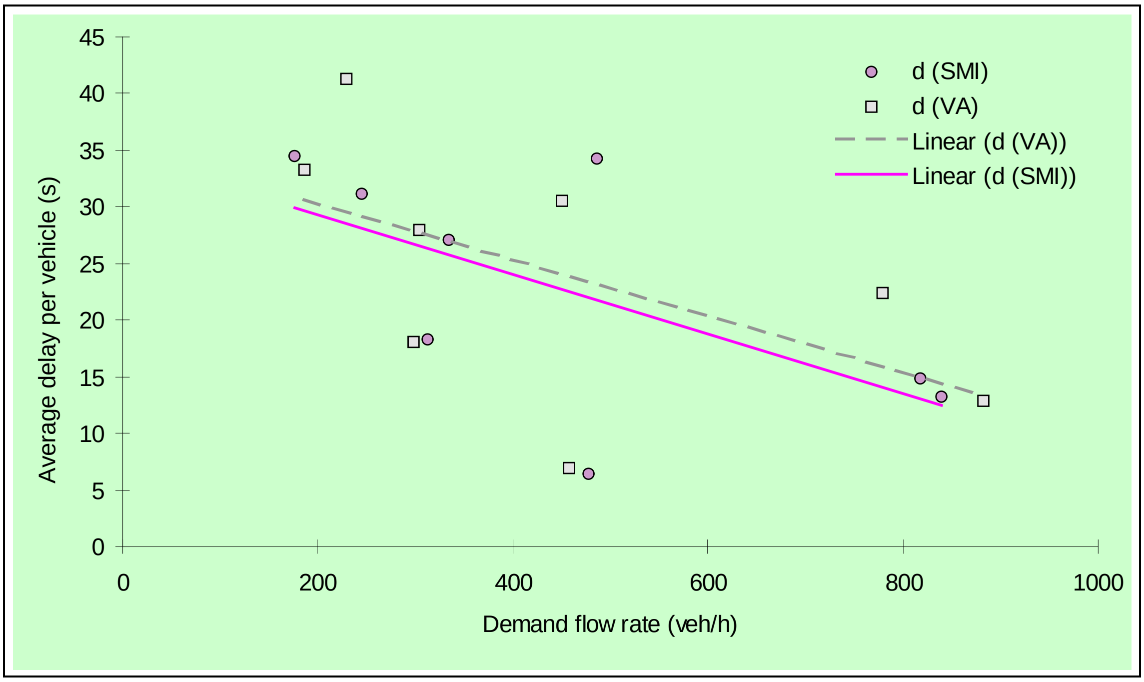

Figure 12 - Comparison of* average lane delays *obtained from SCATS Master Isolated and traditional vehicle-actuated control methods in relation to the average demand flow rate for 90-min peak periods

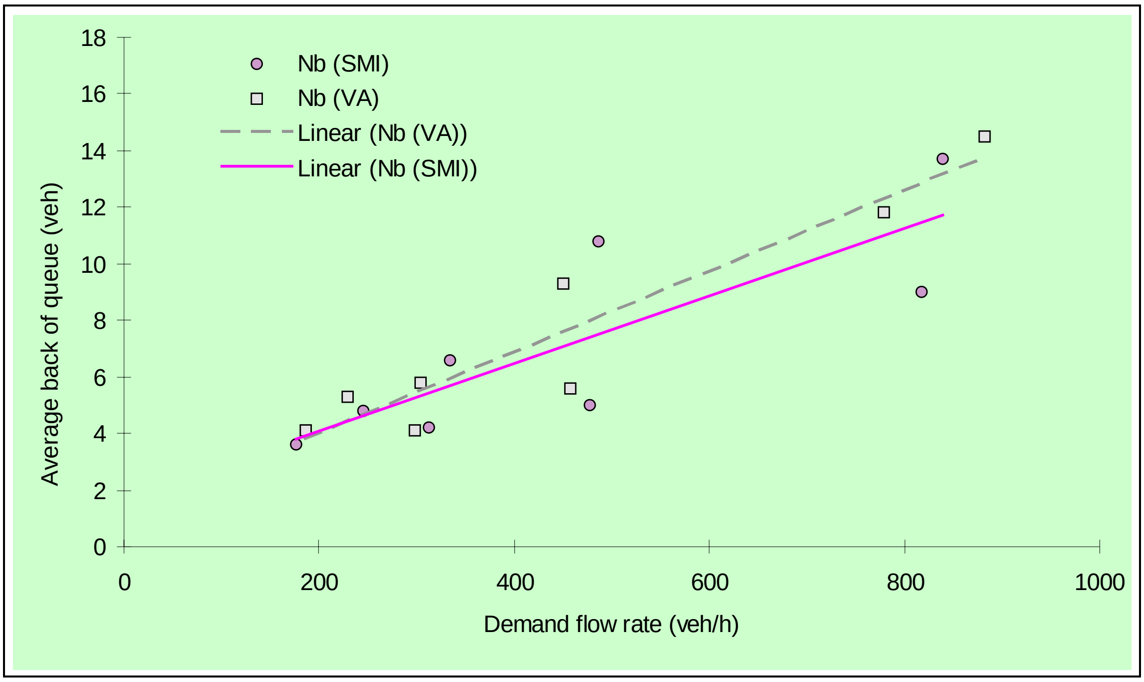

Figure 13 - Comparison of* average back of queue *values for individual lanes obtained from SCATS Master Isolated and traditional vehicle-actuated control methods in relation to the average demand flow rate for 90-min peak periods

Concluding Remarks

Generally, simulation results indicated that Algorithm 9 gave as good or better results than the traditional VA control with appropriate choice of control settings for both control methods. Algorithm 9 did so with a shorter cycle time. The SMI green split method based on the equal degree of saturation (EQUISAT) principle tend to favour major movements. While this generally results in shorter cycle times and reduced major road queue lengths, slightly higher delays to minor movements may result in some cases.

In complicated real-life intersection situations, shorter cycle time means substantial benefits in terms of increased opposed turn, short lane and shared lane capacities, and reduced chance of downstream queue interference. These benefits would mean additional performance gains. Lower cycle times are also preferred in terms of pedestrian delays. For these reasons, Algorithm 9 was considered to offer better overall performance than traditional VA control.

The vehicle-actuated timing method in SIDRA for a typical intersection design with multiple phases shows that very long cycle times (of the order of 180 seconds) may result with typical maximum green time settings (e.g. 60 s for through movements and 20 s for right-turn movements). The results given in this report are for a simple two-phase system. Therefore, SCATS Master Isolated control with its ability to reduce the cycle time, is expected to give larger benefits in real-life cases due to reduced cycle times.

In contrast with the SMI green split method, traditional vehicle-actuated control gives unequal degrees of saturation with lower degrees of saturation and delay for minor movements. Further research has been conducted to investigate effectiveness of SCATS-like algorithms using the Non-EQUISAT principle, i.e. allowing the operator to specify unequal target degrees of saturation for major and minor movements, in order to control relative levels of delay to conflicting movements. Algorithm 10 developed as part of this research produced better results overall compared with Algorithm 9 reported in this paper.

As with delays, the SCATS-like adaptive control algorithms were found to decrease the major road queue lengths substantially. This would decrease the likelihood of upstream intersection blockage and increase short lane capacities, resulting in substantial improvements to the overall traffic system performance.

The surveys at the intersection of Ferntree Gully Road and Scoresby Road produced results that are in line with the results of simulation studies. The overall conclusion is that the SMI control gives better intersection performance than traditional VA control as indicated by lower delays and shorter queue lengths achieved with shorter cycle times. The difference between the performance of the two control methods observed at the intersection of Ferntree Gully Road and Scoresby Road was not large. This is probably due to efficient vehicle-actuated control settings, i.e. short gap time and maximum green settings, used at this intersection.

The simulation results for detector failure cases indicated substantial benefits from the SCATS Master Isolated control method in terms of all performance measures considered. Longer cycle times, higher degrees of saturation and substantially longer delays and queue lengths were observed with the traditional VA control.

Following the first stage of research on SMI control, further work was undertaken to investigate the effectiveness of SCATS-like algorithms for isolated signals using the principle of unequal degrees of saturation. Current research is evaluating SCATS-like algorithms for coordinated signals.

During the research reported in this paper, comparisons of observed values of performance statistics with those predicted by SIDRA (Akçelik and Besley 1998), obtained using the observed timings, demand flow rates and saturation flow rates, were also carried out. SIDRA estimates of intersection performance measures showed that the actuated signal performance models developed in recent years produced satisfactory results (Akçelik and Chung 1995; Akçelik, Chung and Besley 1997).

REFERENCES

AKÇELIK, R. (1994). Estimation of green times and cycle time for vehicle-actuated signals. *Transportation Research Record 1457*, pp 63-72.

AKÇELIK, R. (1995a). *Signal Timing Analysis for Vehicle-Actuated Control*. Working Paper WD TE 95/007. ARRB Transport Research Ltd, Vermont South, Australia.

AKÇELIK, R. (1995b). *Signal Timing Calculation Methods for Vehicle-Actuated and Fixed-Time Signals*. Working Paper WD TO 95/020. ARRB Transport Research Ltd, Vermont South, Australia.

AKÇELIK, R. (1995c). Australian vehicle-actuated control practice: survey results. *Road and Transport Research* 4 (3), pp. 63-70.

AKÇELIK, R. (1997). Fundamental traffic variables in adaptive control and the SCATS DS parameter**.** Paper presented at the *Third International Conference of ITS Australia*, 11-14 March 1997, Brisbane *(CD).*

AKÇELIK, R. and BESLEY, M. (1996). *Fundamental Traffic Flow Relationships at Signalised Intersection Stop-Line*. Working Paper No. WD R 96/043. ARRB Transport Research Ltd, Vermont South, Australia.

AKÇELIK, R. and BESLEY M. (1998). *SIDRA 5 User Guide*. ARRB Transport Research Ltd, Vermont South, Australia.

AKÇELIK, R. and CHUNG, E. (1994). Calibration of the bunched exponential distribution of arrival headways. *Road and Transport Research* 3 (1), pp. 42-59.

AKÇELIK, R. and CHUNG, E. (1995). *Calibration of Performance Models for Traditional Vehicle-Actuated and Fixed-Time Signals*. Working Paper WD TO 95/013. ARRB Transport Research Ltd, Vermont South, Australia.

AKÇELIK, R., CHUNG, E. and BESLEY M. (1997). Recent research on actuated signal timing and performance evaluation and its application in SIDRA 5. *Compendium of Technical Papers (CD)*. 67th Annual Meeting of the Institution of Transportation Engineers, Boston, USA.

CHUNG, E., YOUNG, W. and AKÇELIK, R. (1992). Comparison of roundabout capacity and delay estimates from analytical and simulation models. *Proc. 16th ARRB Conf.* 16 (5), pp. 369-385.

COURAGE, K.G, FAMBRO, D.B., AKÇELIK, R., LIN, P-S., ANWAR, M. and VILORIA, F. (1996). *Capacity Analysis of Traffic Actuated Intersections***.** NCHRP Project 3-48 Final Report Prepared for National Cooperative Highway Research Program, Transportation Research Board, National Research Council.

LOWRIE, P. (1982). The Sydney Coordinated Adaptive Traffic System - principles, methodology, algorithms. *Proceedings of the International Conference on Road Traffic Signalling*. Institution of Electrical Engineers, London, pp. 67-70.

LOWRIE, P. (1990). *SCATS - A Traffic Responsive Method of Controlling Urban Traffic*. Roads and Traffic Authority, Sydney, New South Wales.

TRANSPORTATION RESEARCH BOARD (1998). *Highway Capacity Manual.* Special Report 209, Washington, DC, USA. (*Third edition, Sixth printing, Updated December 1997*).