EVALUATION OF OFF-LINE TRAFFIC-SIGNAL OPTIMIZATION TECHNIQUES

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Four off-line traffic-signal optimization techniques (SIGOP, TRANSYT, Combination Method, and a preferential-street program that is SIGRID-based) were evaluated in both a suburban area and central area network environment within metropolitan Toronto. For each network, fixed-time and time-of-day signal timing patterns were developed for the 7:00 a.m. to 9:00 a.m., 10:00 a.m. to 12:00 noon, 1:00 p.m. to 3:00 p.m., and 4:00 p.m. to 6:00 p.m. time periods. To evaluate the various timing patterns, network travel time, and delay, researchers collected stop and volume data over a 12-week period in the fall of 1973. These data served as the base for a series of comprehensive statistical analyses oriented primarily toward a network evaluation of travel time and service rate. The data later were evaluated by a link-by-link paired comparison analysis. The network analysis of travel time and service rate did not provide conclusive results because of the nature of the study data. On the other hand, the link-by-link paired comparison analyses were more conclusive, relatively simple to use, and easy to interpret. Although the Combination Method settings provided Toronto motorists with a slightly better on-street performance level, any 1 of the 4 methods can provide reasonable signal-network settings.

•OVER the past several years there has been significant progress achieved in the development of off-line optimization programs for pretimed signal networks. The following 3 computer programs are widely regarded as the best approaches available (1):

1. Traffic signal optimization program (SIGOP) (2, 3, 4), which was developed under the sponsorship of the Federal Highway Administration;
2. Traffic network study tool (TRANSYT) (5, 6, 7, 8), which was developed cooperatively by Plessey Automation and the Road Research Laboratory of Great Britain; and
3. Combination Method (9, 10, 11, 12), which was developed by the Road Research Laboratory of Great Britain and later modified by the Greater London Council.

SIGOP contains a split calculation routine in which green times at each signal are computed in proportion to their respective critical-lane flows, total approach flows, or combinations of both. It also contains an offset optimization algorithm that minimizes the discrepancy between the actual signal offsets and a set of given or calculated ideal offsets. The resultant optimized settings are evaluated in terms of delay, stops, and cost values.

TRANSYT consists of a traffic-flow model that computes network flow patterns and associated delay and stop values and allows for platoon dispersion. It also includes a hill-climbing optimization procedure that optimizes splits and offsets alternately by minimizing a network performance index expressed as an aggregate function of link delays and stops. Computing an initial set of splits, which is optional, is based on the Webster method.

The Combination Method, in the form used in this study, does not contain a split computation routine and applies only to condensable networks. Given a set of traffic-signal splits, the program calculates a relationship of delay to difference of offset for each link, and, by combining all of these link functions to form an overall system function of delay to difference of offset, it selects an array of offsets that gives minimum system delay. A combination of delay and stops also may be used as the optimization criterion.

During the fall of 1973, the Metropolitan Toronto Roads and Traffic Department in cooperation with the Ontario Ministry of Transportation and Communications and the Federal Transportation Development Agency compared on-street performance of optimized settings produced by SIGOP, TRANSYT, and the Combination Method with the performance of Toronto's SIGRID-based, fixed-time, time-of-day settings (13). To properly evaluate the various optimization techniques over a range of varying conditions, they selected 4 time periods to cover both peak-hour periods (7:00 a.m. to 9:00 a.m. and 4:00 p.m. to 6:00 p.m.) and representative off-peak periods (10:00 a.m. to 12:00 noon and 1:00 p.m. to 3:00 p.m.). In addition, 2 subnetworks of signals were selected within metropolitan Toronto's grid network of 240 square miles (624 km^2) and 1,100 traffic signals to field test the various signal settings under actual operating conditions. These 2 areas contained a wide range of activities and representative traffic control situations found in most urban areas. The central area subnetwork, as shown in Figure 1, is a grid approximately 2.5 by 1.5 miles (4.0 by 2.4 km) with 68 traffic signals, 174 links, and 245 loop detectors. Within this area, land use varies from high-density commercial activities along Bloor Street to outlying business and medium- to high-density residential neighborhoods between St. Clair and Eglinton Avenues. Traffic signal spacing varies from 460 ft (140 m) to 3,973 ft (1211 m); average spacing is 1,657 ft (505 m). High pedestrian activity and stable volume flows are other typical characteristics of this area.

The second subnetwork is located in a suburban area and contains light industrial-commercial development and relatively low-density residential neighborhoods. Figure 2 shows the 3.5 by 2.5-mile (5.6 by 4.0-km) suburban grid of 51 traffic signals, 114 links, and 257 loop detectors. There are 2 freeways that bisect this subnetwork causing arterial volumes to have a tendency to fluctuate from day to day depending on freeway level of service. Average signal spacing in this area is 2,742 ft (836 m) ranging from 541 ft (165 m) to 6,875 ft (2,096 m).

STUDY METHODOLOGY

For each subnetwork, 3 signal timing plans, encompassing the morning peak period, the evening peak period, and the midday off-peak period, were generated by SIGOP, TRANSYT, and the Combination Method. Rather than predetermine cycle length, we tested a range of cycle lengths for each optimization time period (OTP). However, the magnitudes of the trial cycle lengths were chosen with reference to the existing system and practical constraints such as pedestrian walk requirements and storage problems. The evaluation block within each program was employed to evaluate the potential performance of candidate cycle lengths and associated signal settings. Vehicular delays and stops were used as evaluation criteria, and the optimum solution was the set of cycle lengths, splits, and offsets that provided the lowest system performance index given by total system delay plus 4 times the total number of stops. Table 1 gives a summary of the cycle lengths that were evaluated for each OTP together with the optimum cycle length selected for field evaluation in the central and suburban areas. For each plan, a small number of intersections had to be isolated from the system and be given a higher cycle length to satisfy pedestrian and special phasing requirements. In the case of the Combination Method, a few links were deleted manually from the test subnetworks so that the network could be condensed.

Although the input requirements for the various off-line optimization programs were generally similar in nature from program to program, it is interesting to compare the manpower requirements and computer processing time on Toronto's Univac 1107 system. Knowing these requirements is necessary to prepare typical network traffic-signal plans.

Table 2 gives a summary of average computer time required for processing 1 pro-

Figure 1. Central area subnetwork.

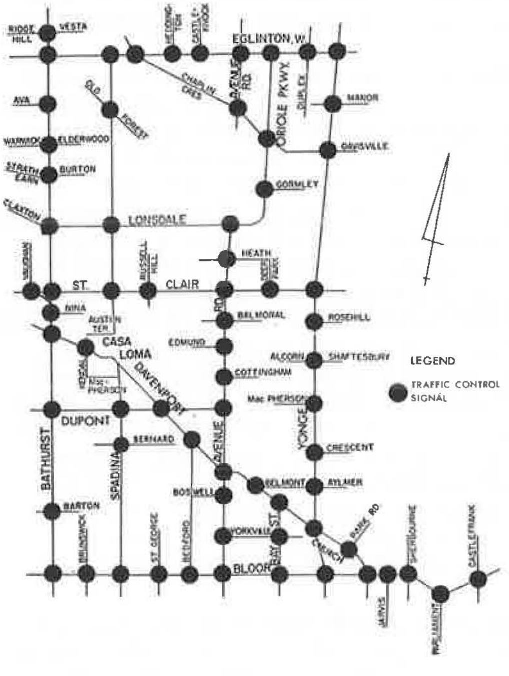


Figure 2. Suburban area subnetwork.

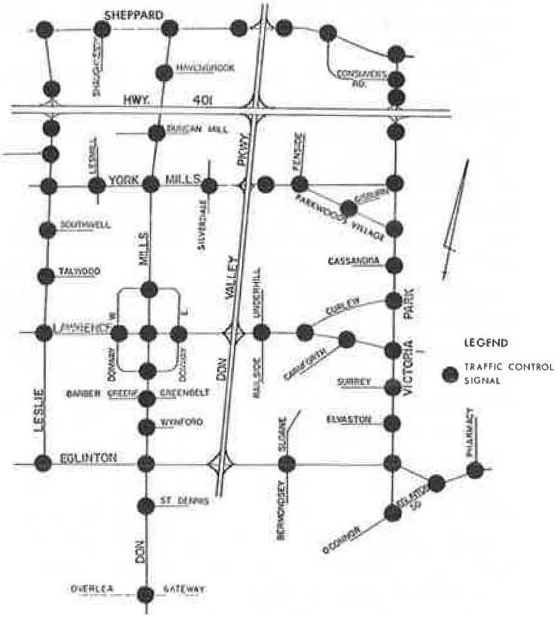


Table 1. Cycle length selection.

		Central Area			Suburban Area		
		Cycle Length (s)			Cycle Length (s)		
Program	Time Period	Tried	Selected	Exceptions	Tried	Selected	Exceptions
Existing plan	Morning peak	–	80	1	–	80 to 110	–
	Off peak	–	60 to 70	0	–	70 to 90	–
	Evening peak	–	80	3	–	70 to 120	–
SIGOP	Morning peak	60, 65, 70, 75, 80, 85, 90	80	1	65, 70, 75, 80, 85, 90, 95, 100	95	2
	Off peak	55, 60, 65, 70, 75, 80	65	0	65, 70, 75, 80, 85, 90	80	4
	Evening peak	70, 75, 80, 85 90, 95	80	3	70, 75, 80, 85, 90, 95, 100, 110, 120	90	7
TRANSYT	Morning peak	80, 90, 100, 120	90	1	95, 100, 110	100	2
	Off peak	60, 65, 70, 80	70	1	70, 80, 90, 100	80	2
	Evening peak	70, 80, 90, 100	90	1	95, 100, 110	100	5
Combination Method	Morning peak	80, 90, 100	80	2	95, 100, 110	100	2
	Off peak	65, 70, 80	70	2	80, 90, 100	80	2
	Evening peak	80, 90, 100	80	2	95, 100, 110	100	3

Table 2. Time requirements for preparing and testing off-line optimization programs.

		Subnetwork Signal Setting Requirements (person hours)			
Program	Average Computer Time per Run (min)	Senior Engineer	Engineer	Technician	Total
SIGOP	12	70	280	360	710
TRANSYT	165	42	250	634	926
Combination Method	6	30	142	715	887
SIGRID	4	10	93	360	463

gram run and the total number of person hours required to prepare both subnetwork signal settings. It should be noted that for TRANSYT and the Combination Method 1 program run was required for each trial cycle length; for SIGOP, however, a range of cycle lengths could be tested within a single program run. Although they are estimated, these figures serve as a useful indicator of the relative cost and effort required in using the computer programs. TRANSYT appears to be the most time-consuming, at least for the networks under study. However, the computer time required for processing TRANSYT is extremely sensitive to the size of the networks. For a small network, it compares favorably with SIGOP and the Combination Method. Although SIGOP seems to require the least coding effort, more effort by professional personnel is necessary because most of the SIGOP input is based on arbitrary decisions and engineering interpretations. On the other hand, the coding of TRANSYT and the Combination Method involves more precise measurements and is relatively routine when the procedure is set up and understood. It also should be noted that the coding effort for SIGOP was lower than normal because the staff involved was familiar with SIGRID, an older version of SIGOP. The Combination Method seems to be the easiest to use, but it does not calculate signal splits. Therefore, additional effort would be needed to prepare the split data. In the Toronto study, the splits as calculated by TRANSYT were used as input to the Combination Method, which reduced overall manpower requirements.

The network settings produced from each of the off-line programs were field tested over a 12-week period in accordance with the schedule given in Table 3. Over this period, data from a comprehensive speed and delay survey were assembled to derive estimates of network performance. Ten field crews were assigned to specific routes during each OTP in both the central and suburban areas. These routes were developed by using a number of general guidelines.

1. Routes should be designed to represent the main flow patterns throughout the test network, including turning movements.
2. High-volume links and links with heavy turning movements should be sampled at least once per OTP.
3. Link samples should be distributed uniformly throughout each OTP.
4. Travel time of all subroutes should not be longer than 20 min in the central area and 30 min in the suburban area. Therefore, 6 sample time periods (STPs) are in each OTP in the central area and 4 STPs are in each OTP in the suburban area.
5. Amount of travel outside the test network should be minimized, but this should not restrict the routes from representing the direction of the major flow.

A typical route layout for one of the 5 speed and delay crews assigned to the suburban area during a certain OTP is shown in Figure 3. Each of the 10 crews consisted of a driver and an observer equipped with 2 stop watches (1 for route time and 1 for stop time), a route map, and a field data form (Fig. 4).

The resultant speed and delay information was edited and merged with real-time traffic volume data from 2 sources (inductive loop detectors and temporary pneumatic counters), and with a complete historical volume file for each link within the 2 subnetworks. The links were classified into 2 types or strata. All links with real-time traffic volume data were categorized under stratum 1. The remaining links were placed in a stratum 2 file because they provided less reliable data. The following gives a summary of the number of links in each strata within the central and suburban subnetworks:

Subnetwork	Real-Time Volume Data	Historical or Extrapolated Volume Data
Central	73	101
Suburban	59	55

Table 3. Schedule of field tests.

Program	Test Period	Reruns
Existing plan	September 24 to 28 October 1 to 5	October 9 and 10
SIGOP	October 15 to 19 October 22 to 26	October 29 and 30
TRANSYT[a]	November 5 to 9 November 13 to 15 November 19	November 20 to 22
Combination Method	November 26 to 30 December 3 to 7	December 10

[a] On November 7, data tape was scratched by malfunctioning tape drive. On November 15, the computer was down.

Figure 3. Suburban area speed and delay route map.

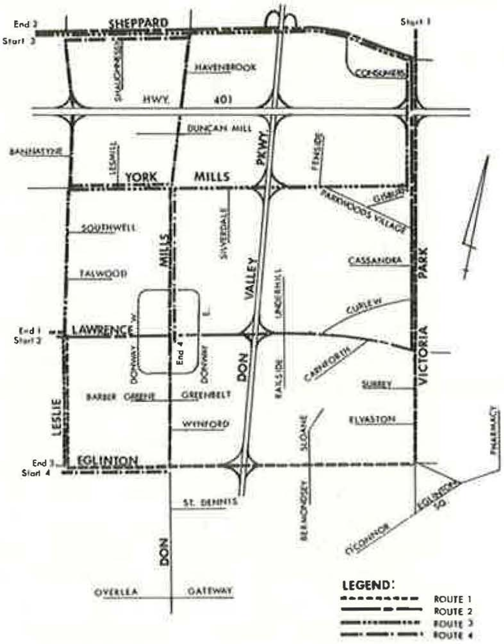
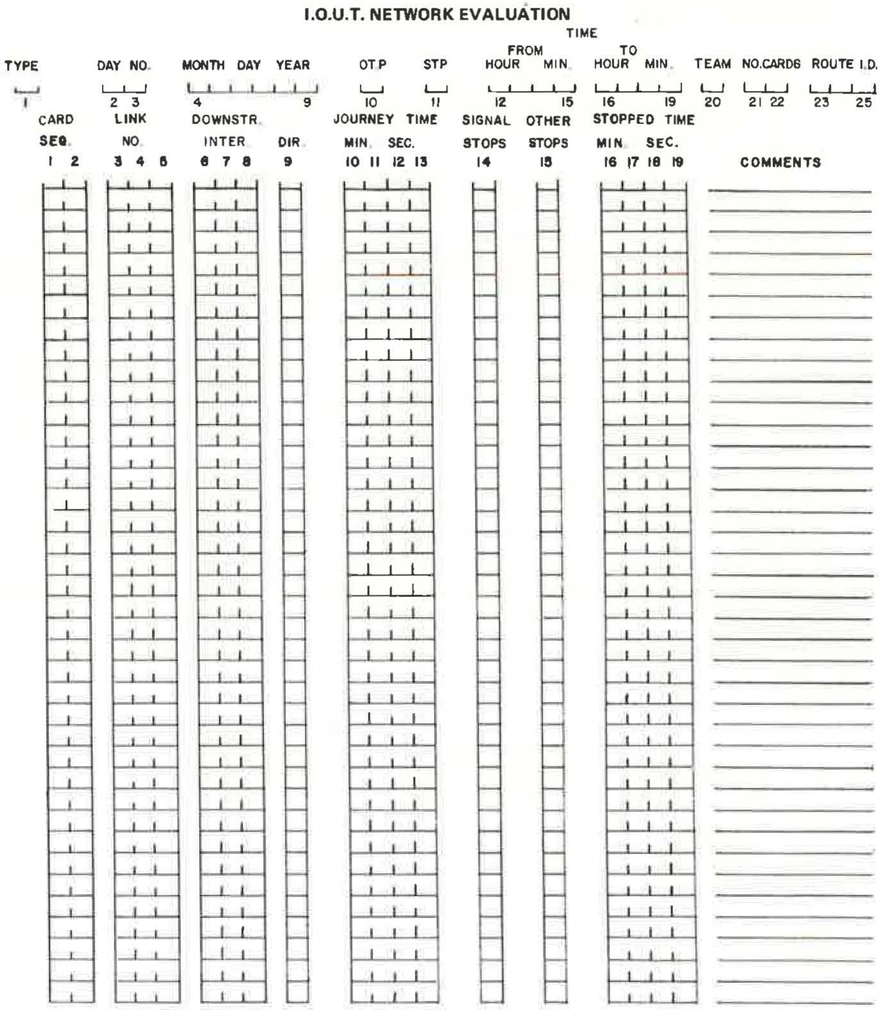


Figure 4. Field data form.



I.O.U.T. NETWORK EVALUATION

TYPE 1

DAY NO. 2 3

MONTH DAY YEAR 4 9

OTP 10

STP 11

TIME FROM HOUR MIN. 12 15

TIME TO HOUR MIN. 16 19

TEAM 20

NO.CARDS 21 22

ROUTE I.D. 23 25

CARD SEQ. 1 2	LINK NO. 3 4 5	DOWNSTR. INTER 6 7 8	DIR. 9	JOURNEY TIME MIN. SEC. 10 11 12 13	SIGNAL STOPS 14	OTHER STOPS 15	STOPPED TIME MIN. SEC. 16 17 18 19	COMMENTS

The real-time traffic volume data then were subjected to a high-low quality-control-limit test. If the real-time count fell below the low limit or above the high limit, either an extrapolated volume or a historical count was substituted. A range of ±4 standard deviations was considered to be a sufficiently wide acceptance limit to permit natural fluctuations of real-time counts without rejection.

ANALYSIS OF DATA

The overall evaluation phase of the study was divided into 2 major components. Initially, a service-rate analysis of network travel time was undertaken (14, 15). However, because of the generally inconclusive nature of the results from this analysis, a link-by-link paired comparison test was carried out afterward.

Service-Rate Analysis

Linear regression analyses were performed on the data, which were stratified by subnetwork; system travel time, in vehicle hours/hour, was the dependent variable, and system service rate in vehicle miles (kilometers)/hour was the independent variable. The data were organized into the following categories:

1. All teams for all OTPs,
2. All teams by OTP,
3. All teams by STP, and
4. Individual OTP and individual plan by team.

The analyses were conducted on network estimates of travel time and service rate based on sample averages per mile (kilometer) and per link by using data from stratum 1 only and from both strata combined. Although the stratum 1 data were considered to be more reliable, analysis results indicated that there was no apparent difference between the 2 sets of data.

Figures 5 and 6 are simplified scatter diagrams of system travel time versus system service rate and derived regression lines for the central and suburban subnetworks. In almost all cases, the regression lines do not exhibit any significant relationships. About 80 percent of the correlation ratios are lower than 0.50, and the regression slopes also are insignificant as shown in Figure 5. The system service rate computed on an OTP basis varies by only a few percent, and this is overwhelmed by the relatively large fluctuations in the system's travel-time values. As a result, data points tend to cluster around the mean. For system service rate computed on an STP basis, a greater range is observed, but the fluctuations in the system's travel-time values also are increased because of greater errors in the network travel-time estimates from a smaller number of link samples. The poor regression results indicate that no valid comparisons based on the regression equations can be made of the different signal timing plans. To complete this phase of the analysis, regression lines also are derived from aggregated plots of data for OTPs 1 to 4 (Fig. 6). Although these regression equations are significant, it is doubtful that they are valid in practice because different OTPs have different traffic behavior, operational characteristics, and signal timing designs.

Although the clustering effects of service-rate data are a weakness for regression analysis, the data lend themselves to a straight comparison of the network travel-time values used in the previously mentioned service-rate analysis. In other words, if the network traffic demand expressed in vehicle miles (kilometers)/hour during a particular OTP on a certain day is not significantly different from that on another day, then the respective network travel times expressed in vehicle hours/hour can be compared directly and tested for significant differences. To ensure that network demand is relatively constant, the service rates for different plans were paired and tested for significant differences by Student's t-test for difference of means. As indicated in the data given in Table 4, almost no significant differences in the network vehicle miles (kilo-

Figure 5. Regression analysis per mile for OTP 1, all teams and STPs: (a) central area and (b) suburban area.

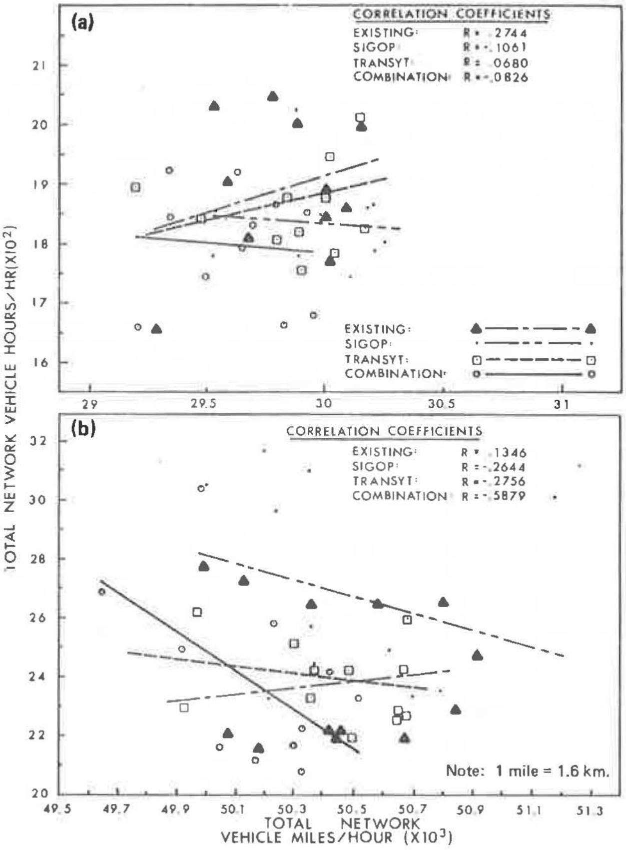
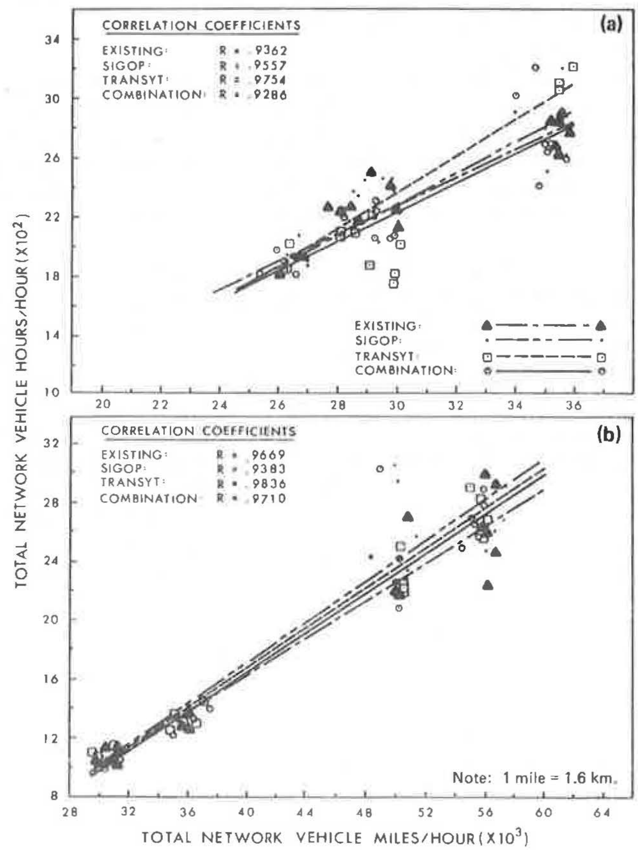


Figure 6. Regression analysis per mile for all OTPs, teams, and days: (a) central area and (b) suburban area.



meters)/hour were detected among all the signal plans for all test periods. It therefore was felt that a straight comparison of network vehicle hours/hour was justified. The results of the straight comparison test, as given in Table 5, indicate that there was no significant difference among the signal plans in terms of their effectiveness. There are however 2 exceptions—between TRANSYT and the existing plan and between the Combination Method and the existing plan during the evening rush period. During this period, TRANSYT seemed to be significantly less effective than the existing plan and the Combination Method.

Based on these findings, the service-rate analysis technique does not appear to be sufficiently sensitive to actual differences (if any) among the alternative signal plans. The effect of vehicular volume and the aggregation of field data may have had the most significant effect on the data results. Because vehicular volume in vehicles/hour is part of the dependent as well as the independent variable, the independent variable in vehicle miles (kilometers)/hour is not truly independent. In addition, errors in link travel-time measurements and network estimates may greatly influence the data such that travel-time differences between the various signal plans are rendered insignificant. Thus we felt that a more sensitive statistical routine for the comparison of signal plans must be used for this study.

Paired Comparison Analysis

For the reasons outlined above, a link-by-link paired comparison analysis based on Student's t-test for mean of differences was carried out on both link volume and link travel time. SIGOP, TRANSYT, and Combination Method data were compared against Toronto's existing fixed-time, time-of-day signal plans, thus minimizing the number of tests to be carried out. The links were compared on a 1-to-1 basis over a similar time period. To determine which links had no significant change in volume, a t-test at a 1 percent significance level was employed. The nature of this test required that a population (in this case an STP or an OTP) be totally accepted or rejected. Although the test was a link-by-link comparison, a complete OTP or STP had to be tested as a unit for volume comparison. When the time periods with significant volume differences had been eliminated, a t-test on link travel time at a 5 percent significance level was carried out on the remaining data.

Table 6 gives a summary of the results of the paired comparison tests on link volume. At a 1 percent significance level, the rejection rate was generally higher on an OTP basis than an STP basis because an STP with significantly different volumes could cause the rejection of an entire OTP data set. In all cases, the accepted data were more than adequate to continue a paired comparison analysis for link travel time.

In terms of the travel time, the Combination Method provided a slightly better level of service than the other 3 methods did (Table 7). For example, on an OTP basis in the central area, the Combination Method produced a 4.5 percent improvement in system travel time over the existing plan; TRANSYT and SIGOP increased travel time over existing times by 0.64 and 0.75 percent respectively. In the suburban area, the Combination Method on an OTP basis produced a 2.8 percent improvement over the existing plan, which in turn effected travel time reductions of 3.0 percent over TRANSYT and 3.2 percent over SIGOP.

SUMMARY AND CONCLUSIONS

In SIGOP, signal splits are calculated from critical lane flows or total approach flows without allowing for the capacity or saturation flow characteristics of the lanes or approaches. The program requires the use of many arbitrary factors, and the instructions for choosing their appropriate values are, for the most part, not presented clearly in the program manual. Most of these factors do not have any apparent theoretical basis; the success of their use depends on the interpretation and judgment of the user. The program also has a number of oversimplifying assumptions that tend to reduce its

Table 4. Comparison of system service rate for no significant difference.

		Significant Difference											
		SIGOP				TRANSYT				Combination Method			
Subnetwork	Program	OTP1	OTP2	OTP3	OTP4	OTP1	OTP2	OTP3	OTP4	OTP1	OTP2	OTP3	OTP4
Central	Existing plan	No	No	No	No	No	No	No	No	No	No	No	No
	SIGOP	—	—	—	—	No	No	No	No	Yes[a]	No	No	No
	TRANSYT	—	—	—	—	—	—	—	—	No	No	No	No
Suburban	Existing plan	No	No	No	No	No	No	No	No	Yes[a]	No	No	Yes[a]
	SIGOP	—	—	—	—	No	No	No	No	No	No	No	Yes[a]
	TRANSYT	—	—	—	—	—	—	—	—	No	No	No	No

[a] Significant at the 1 percent level.

Table 5. Comparison of system travel time for a 5 percent significant difference.

		Significant Difference											
		SIGOP				TRANSYT				Combination Method			
Subnetwork	Program	OTP1	OTP2	OTP3	OTP4	OTP1	OTP2	OTP3	OTP4	OTP1	OTP2	OTP3	OTP4
Central	Existing plan	No	No	No	No	No	No	No	Yes[a]	No	No	No	No
	SIGOP	—	—	—	—	No	No	No	No	NT[b]	No	No	No
	TRANSYT	—	—	—	—	—	—	—	—	No	No	No	Yes[a]
Suburban	Existing plan	No	No	No	No	No	No	No	No	NT[b]	No	No	NT[b]
	SIGOP	—	—	—	—	No	No	No	No	No	No	No	NT[b]
	TRANSYT	—	—	—	—	—	—	—	—	No	No	No	No

[a] Significant at the 5 percent level.

[b] No test undertaken because of significant difference in system service rate.

Table 6. Summary of paired comparison results for link volume.

			Samples With Significant Difference (percent)		
Subnetwork	Time Period	Sample Size	Existing Plan Versus SIGOP	Existing Plan Versus TRANSYT	Existing Plan Versus Combination Method
Central area	OTP	40	25.0	27.5	42.5
	STP	240	11.7	19.6	20.0
Suburban area	OTP	40	12.5	27.5	35.0
	STP	160	15.0	26.2	22.5

Table 7. Central and suburban area paired comparison results for link travel time.

			Samples Tested		Significant Difference (percent)		Travel Time Difference			Time Improvement	
Time Period	Comparison	Total Samples	Number	Percent	Yes	No	Hour	Minute	Second	Percent	Plan
Central Area											
OTP	Existing plan versus SIGOP	40	29	72.0	17.2	82.8	0	23	4	0.75	Existing
	Existing plan versus TRANSYT	40	28	70.0	14.3	85.7	0	19	7	0.64	Existing
	Existing plan versus Combination Method	40	23	57.5	34.8	65.2	1	49	53	4.5	Combination
STP	Existing plan versus SIGOP	240	205	85.4	8.8	91.2	0	38	50	0.47	Existing
	Existing plan versus TRANSYT	240	192	80.0	10.4	89.6	0	56	1	0.71	Existing
	Existing plan versus Combination Method	240	191	79.6	13.6	86.4	3	50	33	2.9	Combination
Suburban Area											
OTP	Existing plan versus SIGOP	40	34	85.0	29.4	70.6	1	48	15	3.2	Existing
	Existing plan versus TRANSYT	40	28	70.0	28.6	71.4	1	25	41	3.0	Existing
	Existing plan versus Combination Method	40	24	60.0	29.2	70.8	1	9	42	2.8	Combination
STP	Existing plan versus SIGOP	160	135	84.4	20.7	79.3	4	48	42	3.4	Existing
	Existing plan versus TRANSYT	160	119	74.4	26.1	73.9	3	1	42	2.5	Existing
	Existing plan versus Combination Method	160	122	76.3	18.0	82.0	2	29	4	2.0	Combination

effectiveness as a signal optimization model. For example, vehicular arrivals at downstream intersections are assumed to follow a square wave pattern; platoon dispersion effects are not considered.

Despite these weaknesses, SIGOP performed surprisingly well according to the Toronto results mainly because the study personnel were experienced in using the test signal system. They also were familiar with SIGRID, a predecessor of SIGOP. So it was relatively easy for them to interpret the program manual and choose appropriate values for the various arbitrary factors required as input to the program. Also any unreasonable output from the program was detected easily and corrected by making the necessary adjustment in the program input. Because of the arbitrary nature of SIGOP, familiarity with both the program and the system is such an important factor that it could well explain why SIGOP has been used with varying degrees of success.

TRANSYT has been regarded as a logical and theoretically sound program. Its success has been demonstrated in a number of research studies (1). The strength of this program lies in its traffic-flow model that accurately traces flow patterns from signal to signal and allows for the effects of platoon dispersion by means of a platoon prediction model.

However, the superiority of TRANSYT was not evident from the results of the Toronto study. This perhaps occurred because the program was used without prior calibration of some of the program parameters for local conditions (such as the smoothing factor used in the platoon dispersion model). This would have reduced the effectiveness of the program. For example, in a subsequent and separate study in Toronto (16), Robertson's platoon dispersion model was found to be satisfactory, but the parameters had to be calibrated to suit local conditions to obtain the best fit between actual and predicted platoon structures. Because TRANSYT was not found to be decisively inferior to the other programs, one expects that it would perform much better if the program were calibrated.

The Combination Method contains a flow model similar to that existing in TRANSYT, but its optimization process is radically different. It is assumed that no flow continuity exists between links; each link is treated as a separate entity with its own distinct relationship of delay to difference of offset. This influences the program's effectiveness in dealing with undersaturated signals where vehicular queues seldom exist. The Combination Method is not a comprehensive signal optimization package because it does not calculate signal splits. However, this permits the user to intervene freely and introduce his or her own judgment in screening the split data input prior to program execution. This may be the primary reason for the slightly better performance of the Combination Method in some cases.

The Toronto study results also indicated that the existing signal settings compared favorably with those obtained from the sophisticated computer program packages. This was expected because the existing timings are the results of years of experience with the signal system and continuous engineering efforts.

All of the signal timing plans provided similar levels of service in the test subnetworks based on the analysis of travel time. It should be noted, however, that the various signal optimization programs are based on the criteria of delay and stops, which may constitute only a minor proportion of total system travel time, particularly for a large network with relatively long links and smooth flow characteristics.

Whichever optimization program is chosen to design urban network signal settings, the user must have a thorough understanding of the selected program and a comprehensive knowledge of the signal system. In addition, a commitment must be made to carefully review the program output to ascertain its validity. Although these off-line signal optimization programs can be used as engineering aids in network signal-setting design, they should not be used as replacements for engineering judgment and expertise.

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