Signal Networks

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With the conclusion of World War II there came an unprecedented growth in the number of motor vehicles on the streets of our cities. To meet the challenge, traffic engineers looked to various means of improving the tools already at hand. The traffic control signal was already taking its place at the head of the list of devices which could be used to regulate and promote more orderly traffic flow. However, as more and more traffic signals began to appear, it became evident that the disruption to traffic flow caused by frequent stops along any route was undoing the benefits which would otherwise be derived.

From necessity, there soon evolved several examples of linked signals, which were coordinated to provide a greater degree of continuity in traffic flow. These groups of linked signals are called "networks."

The methods of linking varied widely, however, a method which is still used extensively today involves the use of an interconnecting cable joining the several traffic signal control units which are to be linked. One of the units serves as a master, and the balance are slaves. The function of the master is merely to maintain the established synchronization between each of the units.

Later developments involved centralized control. In the earlier examples, the central control provided for greater flexibility by permitting a larger number of timing cycles than was normally accommodated by the intersection control units. Central control also permitted greater flexibility in selecting the time at which changes in signal timing were to go into effect.

The next evolutionary step was almost predictable. The selection of the time at which various signal timing arrangements would go into effect had been predetermined and activated by time clocks; with the advent of devices which could detect traffic flow on the streets it became practicable to permit the selection of various signal timing arrangements to be activated by the changes in actual traffic flow. The development of the electronic arts produced the necessary devices for measuring the traffic flow. The means were now at hand to provide for a direct link between actual traffic flow and the selection of various pre-arranged signal timing patterns. So it was that there appeared a new central traffic signal control, which was generically called an "analog computer." Through this type of control a giant step was taken in harnessing the traffic signals in a manner more sensitive to actual traffic demands than had previously been the case.

In June 1963, the Municipality of Metropolitan Toronto created a central control system for a signal network that was to encompass all of the signals in the metropolitan area. To accomplish this task, a very large "digital" computer was installed, which was connected to every signal control unit through leased telephone line. In addition, a large number of vehicle detectors were installed to provide the computer with actual traffic flow data. This was the first time that a digital computer was used for this type of task.

One of the advantages in using a digital computer was the fact that it has no built-in traffic control functions, but must be specifically programmed for each task. As a result, it was possible to arrange for network operation and single intersection operation in various modes and thus compare the effect on traffic flow of each method. For the first time a realistic comparison and appraisal could be made by actual field trials of various modes of operation rather than relying on theoretical analyses or simulation techniques.

The centrally controlled traffic signal system was not specifically to be a research tool, although the possibilities for this were very great. It was basically to be an

EFFECT OF DIFFERENT MODES OF SIGNAL OPERATION ON TRAFFIC CONDITIONS AS SHOWN BY

Street Name	Street Type	No. of Signals	Length (mi)	Average Travel Time (min)							Average Speed		
				Random	Coordinated Pre-Timed	Change (%)	Coordinated Traffic Responsive	Change (%)	Improved Traffic Responsive	Change (%)	Random	Coordinated Pre-Timed	Change (%)
University Avenue	6-Lane arterial	13	1.7	6.15	4.85	-21.2	5.14	-16.8	4.28	-30.4	16.6	21.1	+27.0
Yonge Street	4-Lane arterial	42	10.8	36.97	39.73	+ 7.5	37.26	+ .8	36.68	- .7	17.6	16.3	- 7.4
Mt. Pleasant Road and Jarvis St.	4-Lane arterial with street cars	25	5.6	20.74	16.93	-18.4	18.55	-10.6	17.27	-16.7	16.2	19.9	+22.8
Broadview Avenue and O'Connor Dr.	4-Lane arterial	11	4.2	14.95	11.10	-25.8					16.8	22.6	+35.4
St. Clair Ave. W.	4-Lane arterial with street cars	20	4.5	15.94	13.50	-15.2					16.9	20.0	+18.4
St. Clair Ave. E.	2-Lane arterial	9	2.9	7.50	7.03	- 6.3					23.2	24.8	+ 6.9
Dundas Street E.	4-Lane arterial	13	3.0	9.57	8.25	-13.8					18.8	21.9	+16.5
Davenport Road	4-Lane arterial	9	2.7	9.32	7.35	-21.0					17.4	22.0	+26.4
Gerrard Street E.	4-Lane arterial with street cars	17	4.6	16.88	15.67	- 7.2					16.3	17.6	+ 8.0
Average values per mile of roadway		4	4.4	3.5	3.1	-11.4	3.3	- 5.7	3.2	- 8.6	17.1	19.4	+13.4

Note: During the period covered by these studies the number of vehicles registered in Metropolitan Toronto increased by 9.6 percent, whereas the number of reported motor vehicle accidents increased by

operational system in which advantage would be taken of the latest techniques in operating a network of signals. To determine the optimum or most desirable methods of controlling traffic flow, the computer was programmed to permit trying several techniques. The base for comparison was a random operation of all the existing signals. The elements recorded were speed and delay, number of stops, and accidents.

TRAVEL TIME WITH NETWORK SIGNAL CONTROL—LINEAR NETWORK

The first program controlled a coordinated signal system on 9 routes. These routes were programmed as linear networks; i. e., each route was optimized for through travel, with no regard for intersecting routes. However, they were all two-way streets which would require bi-directional consideration. The total number of signals involved was 159. There was an average of 4 signals per mile for some 40 miles. The results of these tests are shown in Table 1, and a representative sample of the results is shown in Figure 1. The improvement in travel time varied from 6. 3 to 25. 8 percent on eight of the nine routes. On one route there was an actual loss in travel time of 7. 5 percent. The average improvement on the nine routes was 11. 4 percent.

These tests also showed a reduction in the number of involuntary stops averaging 43. 8 percent. On individual routes the reduction in involuntary stops varied from no change to a reduction of 58 percent.

GRID NETWORK

The next stage of development involved a two-fold change. First, three of the previously mentioned routes were programmed in a grid network; i. e., consideration was also given to through movement on the cross routes. Second, the timing and directional patterns were activated by traffic flow on the vehicle detectors rather than by a pre-timed basis. As can be expected, the average travel time on the three routes was not as good as when they were programmed as a linear network.

By this time, however, Toronto had progressed in familiarity with the digital computer to the stage where the machine could be used to formulate the signal timing schemes. The computer was, therefore, used to develop an optimized timing arrangement for the grid network and the results (Table 1) indicate the improvement which followed. On one route the reduction in travel time was 21. 2 percent with a linear network, 16. 8 percent with the grid network, and 30. 4 percent with the improved grid network. In addition, during the interval of time between the tests of the random timing and the improved grid network there had been a vehicle volume growth of approximately 9. 6 percent.

:D AND DELAY STUDIES AND ACCIDENT ANALYSIS ON VARIOUS SUBURBAN ARTERIAL STREETS

		Number of Involuntary Stops							Number of Vehicle Accidents per Year: Total Accidents			Accidents at Intersections			Accidents Between Intersections		
nproved Traffic esponsive	Change (%)	Random	Coordinated Pre-Timed	Change (%)	Coordinated Traffic Responsive	Change (%)	Improved Traffic Responsive	Change (%)	Before Control	After Control	Change (%)	Before Control	After Control	Change (%)	Before Control	After Control	Change (%)
23.8	+43.1	4.8	2.0	-58.0	3.2	-33.4	2.1	-56.0	201	185	- 8.0	174	157	- 9.8	27	28	+ 4.0
17.7	+ .6	19.1	13.2	-30.6	10.9	-42.8	10.8	-43.5	949	1012	+ 6.7	658	762	+15.8	291	250	-14.1
19.5	+20.4	10.0	4.2	-58.0	6.4	-36.0	5.9	-41.0	410	363	-11.4	316	259	-18.0	94	104	+ 9.6
		5.4	2.1	-61.0					146	132	- 9.6	119	90	-24.4	27	43	+59.2
		6.5	3.5	-46.2					625	590	- 5.6	466	417	-10.5	159	173	+ 8.8
		1.8	1.8	Nil					154	150	- 2.6	108	117	+ 8.3	46	33	-28.3
		3.8	2.1	-44.8					205	201	- 1.9	159	148	- 6.9	46	53	+15.2
		3.8	3.1	-18.5					213	257	+20.6	182	218	+19.8	31	39	+25.7
		7.7	4.8	-37.7					247	280	+13.3	163	191	+17.2	84	89	+ 5.9
18.8	+ 9.9	1.6	.9	-43.8	1.1	-31.2	1.0	-37.5	79	80	+ 1.2	59	59	Nil	20	20	Nil

TRAFFIC ACCIDENTS

A comparison of accident experience was made on the nine routes in the original study area. The results of the accident comparison are also given in Table 1.

The total number of accidents on the nine routes did not change during the test period. However, accidents generally went up by 10. 6 percent during the period. Further analysis is necessary to verify whether system operation has a significant effect on traffic accidents.

COORDINATED NETWORK WITH TRAFFIC-RESPONSIVE SPLIT SELECTION

The next stage in the improvement of the network signal control was the provision of traffic-responsive adjustment of the cycle split at major intersections while maintaining the network cycle and coordination. This would not affect the travel time on the route to any great extent, but could affect the congestion at each intersection.

It had been observed that, even during the period of heaviest traffic flow, there was a cycle-by-cycle variation in the number of vehicles arriving at any intersection. The number of arrivals per cycle was observed to vary by as much as 50 percent. It would seem to be logical, therefore, that the proportion of green time should vary cycle by cycle in order to take advantage of the varying number of arrivals. The computer was, therefore, programmed to provide the network coordinated control, as previously described, with the added capability of permitting the proportion of green to be varied within the system cycle length in accordance with traffic detections at each of the intersections so affected. Testing was performed to validate this arrangement.

CONGESTION AT INTERSECTIONS

For the most part, the vehicle detectors are located approximately 300 ft from the signalized intersection. The number of vehicles that could store in this distance is normally able to clear on the next green light. Congestion is, therefore, indicated when the queue extends beyond the detector and, as a result, movement over the detector is very slow. For comparative and test purposes, congestion has been arbitrarily defined as the condition prevailing when traffic flow across the detector falls below 12 mph. At the same time, to insure that the slow movement is due to congestion and not some other factor, the computer is directed to accept only those indications of slow traffic when the volume rate is in excess of 250 veh/hr per approach. These parameters of speed and volume are derived by the computer from measurements of the pulses generated at the loop detectors.

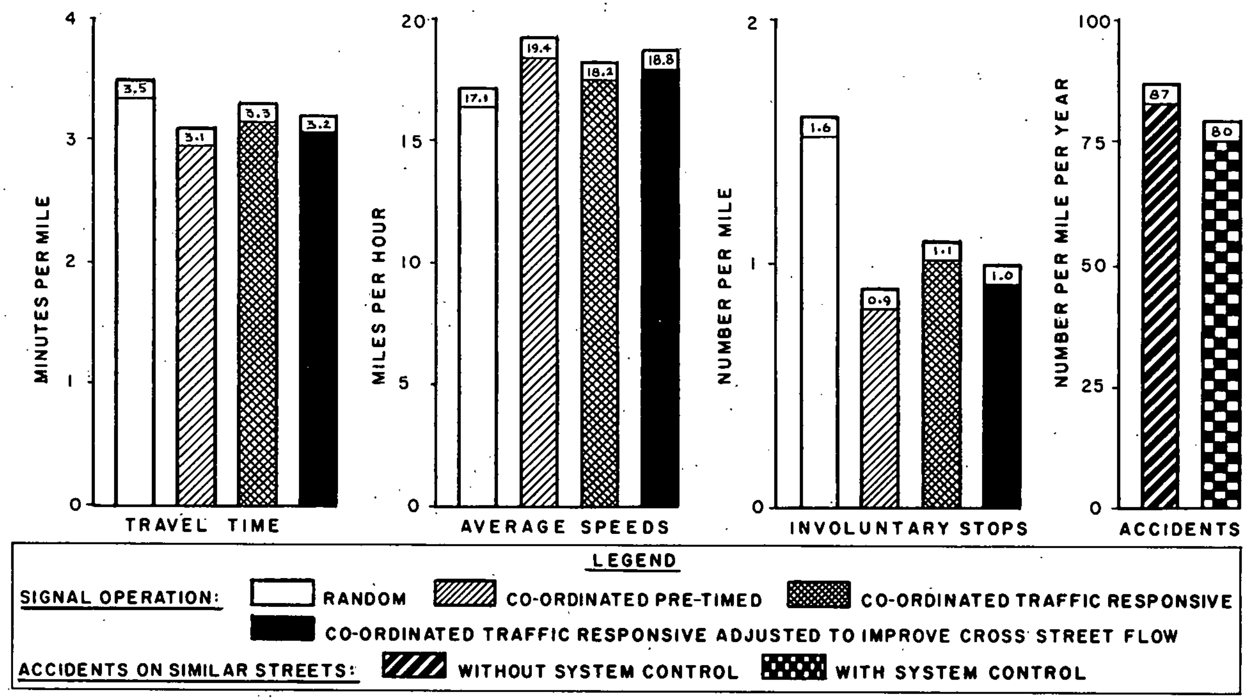

Figure 1. Overall effect of different modes of signal operation on traffic conditions as shown by floating car speed and delay studies and accident analysis.

TABLE 2

COMPARISON BETWEEN THE EFFECT OF PREDETERMINED AND COORDINATED TRAFFIC-RESPONSIVE SIGNAL OPERATION AT VARIOUS LOCATIONS

Intersection	Time of Day	Coordinated Predetermined			Coordinated Traffic Responsive			Percent Change		
		Congested Cycles (%)	Volume, All Approaches (veh/hr)	Volume, Two Critical Approaches (veh/hr)	Congested Cycles (%)	Volume, All Approaches (veh/hr)	Volume, Two Critical Approaches (veh/hr)	Congested Cycle	Volumes, All Approaches (veh/hr)	Volume, Two Critical Approaches (veh/hr)
Church-Bloor	7:30-9:30	63	2434	1521	36	2614	1693	-43	+7.4	+11.3
Jarvis-Wellesley	7:30-9:30	21	2633	1997	6	2701	2040	-71	+2.6	+ 2.1
Jarvis-Carlton	7:30-9:30	14	2558	1738	11	2409	1718	-21	-5.8	- 1.2
Yonge-College	7:30-9:30	33	2360	1343	29	2390	1360	-12	+1.3	+ 1.3
Yonge-Lawrence	7:30-9:30	47	3259	1956	8	3278	1975	-83	+0.6	+ 1.0
Jarvis-Dundas	7:30-8:00	45	2167	1461	33	2193	1483	-27	+1.2	+ 1.5
Jarvis-Dundas	8:00-8:30	60	2552	1659	35	2574	1683	-42	+0.9	+ 1.4
Jarvis-Dundas	8:30-9:00	43	2430	1560	31	2456	1587	-28	+1.1	+ 1.7
Jarvis-Dundas	9:00-9:30	18	2185	1361	17	2245	1402	- 6	+2.7	+ 3.0
Average		38.2	2509	1622	22.9	2540	1660	-40	+1.3	+ 2.3

The percentage of congested cycles at nine major intersections was compared during the morning rush hours. The comparison is between conditions existing when the coordinated network operation was using predetermined cycle splits as against conditions when the cycle splits were varied in response to traffic actuation. The results of this test are given in Table 2 and indicate that in every case the number of congested cycles was less when traffic actuations varied the split of green time. The improvement was 40 percent fewer congested cycles. Figure 2 shows the improvement at some selected intersections.

FULLY TRAFFIC-RESPONSIVE SIGNAL OPERATION

Experience to this date has shown that there are usually a few critical intersections in the grid network, at which a queue will develop during the peak traffic flow which nullifies the effect of coordination as far as continuous traffic flow is concerned. When this occurs, the value of retaining such intersections within the coordinated network is very dubious. Experiments have therefore been conducted with dropping such a signal out of coordination and operating it as a fully traffic-responsive isolated intersection. Under this scheme, the signal has freedom to vary its split and cycle almost infinitely. Each green phase is permitted to extend itself until the advantage of further extension is nullified by the increased vehicle delay on the red phase. The cycle is made up of the sum of the green phases. Within the limited experience, it would seem that a series of intersections operating in this manner would tend to coordinate themselves by platoon recognition.

Figure 3 shows the effect on queue length at a test intersection, achieved by fully traffic-responsive operation. The advantage is principally achieved by optimizing capacity and by balancing delay between all approaches. A similar improvement in the average approach density at the test intersection is shown in Figure 4.

THE DIGITAL COMPUTER AS A STUDY TOOL

An important advantage in the use of a digital computer for traffic control is related to its inherent ability to be used for study and analysis purposes. In this way, the traffic engineer can quickly be made aware of the effectiveness or non-effectiveness of any traffic control changes. At this time, a library of thirteen analysis programs and six data preparation programs has been developed. These programs are designed to search the magnetic tapes storing a detailed record of all the events reported to the computer during routine control operation. The tape contains a second-by-second record of the aspect of every signal under control, traffic count, and pulse length at each detector. From this, one can arrange for graphical or tabular summaries of traffic counts, space-time diagrams, volume-lane occupancy graphs, and numerous other presentations of the data.

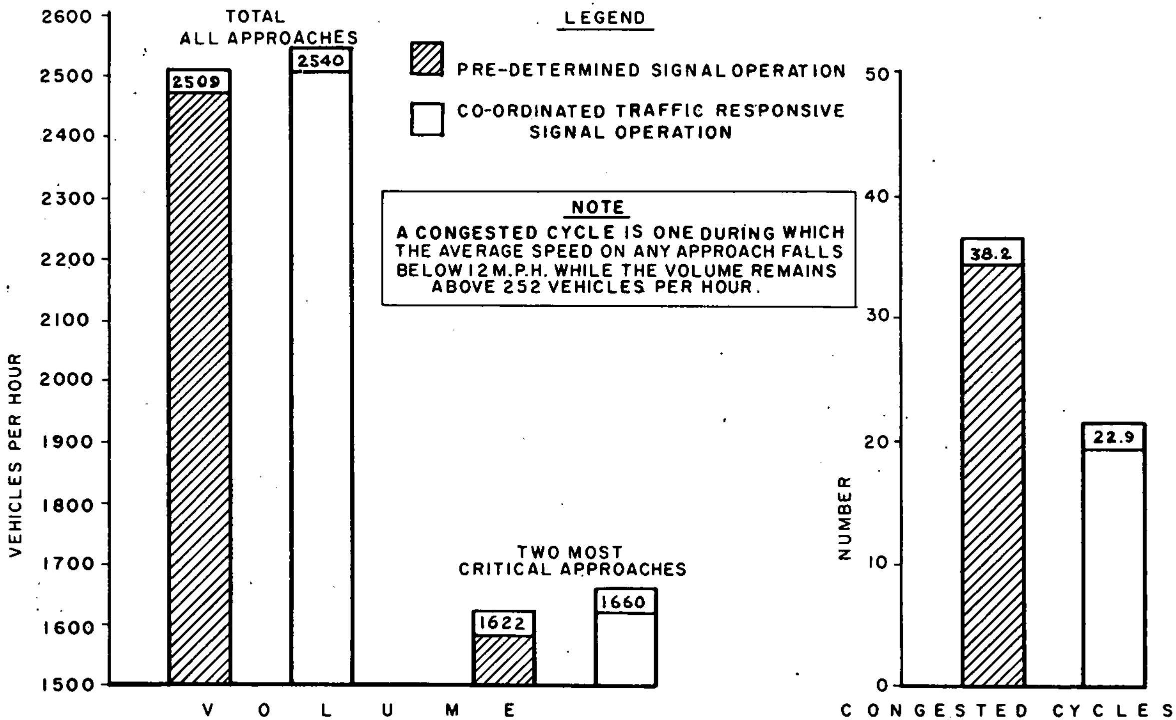

Figure 2. Overall comparison between the effect of predetermined and coordinated traffic-responsive signal operation.

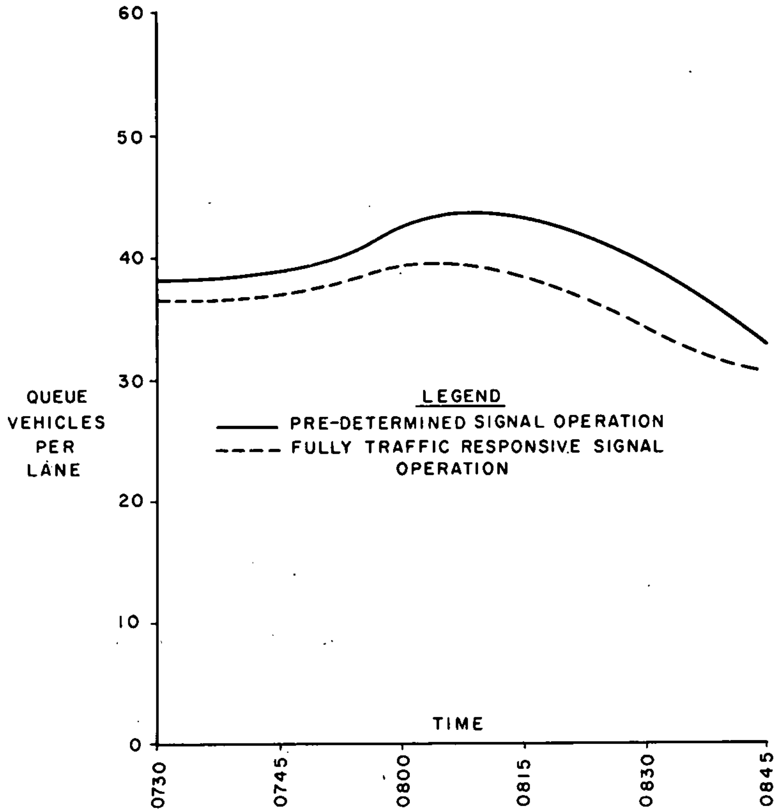

Figure 3. Comparison between the effect of predetermined and fully traffic-responsive signal operation as shown by the measurement of average queue length at a single intersection.

SPACE-TIME DIAGRAM

Figure 5 is a printout taken from the computer of actual signal operation of ten signals in a coordinated linear network. The time of operation is between 7:30 a. m. and 7:45 a. m. The traffic flow is predominantly southbound and the printout shows the progression available to each direction of traffic. Figure 6 shows a printout in which one intersection controller was deliberately dropped from coordination. The effect on the progression through the area is immediately discernible.

TIMING PLAN CHANGES

Figure 7 is a printout of two adjacent signals. The location is in the vicinity of the Maple Leaf Gardens on a night of a National Hockey League game. The printout at the left depicts variations in traffic volumes at a location used to trigger changes in signal timing for the network in the vicinity of the hockey arena. The reaction to the release of the large volume of traffic after the game can be seen by the plan changes, which take place during the evening. The printout at the right illustrates the similarity of traffic flow at an adjacent intersection which forms part of the network affected by the plan changes. Figure 7 is representative of traffic-responsive network operation.

Another example of the value which can accrue to traffic movement at a single intersection resulting from the ability of the system to select various timing plans as traffic demands vary is shown in Figure 8. The printout of derived density, taken from the

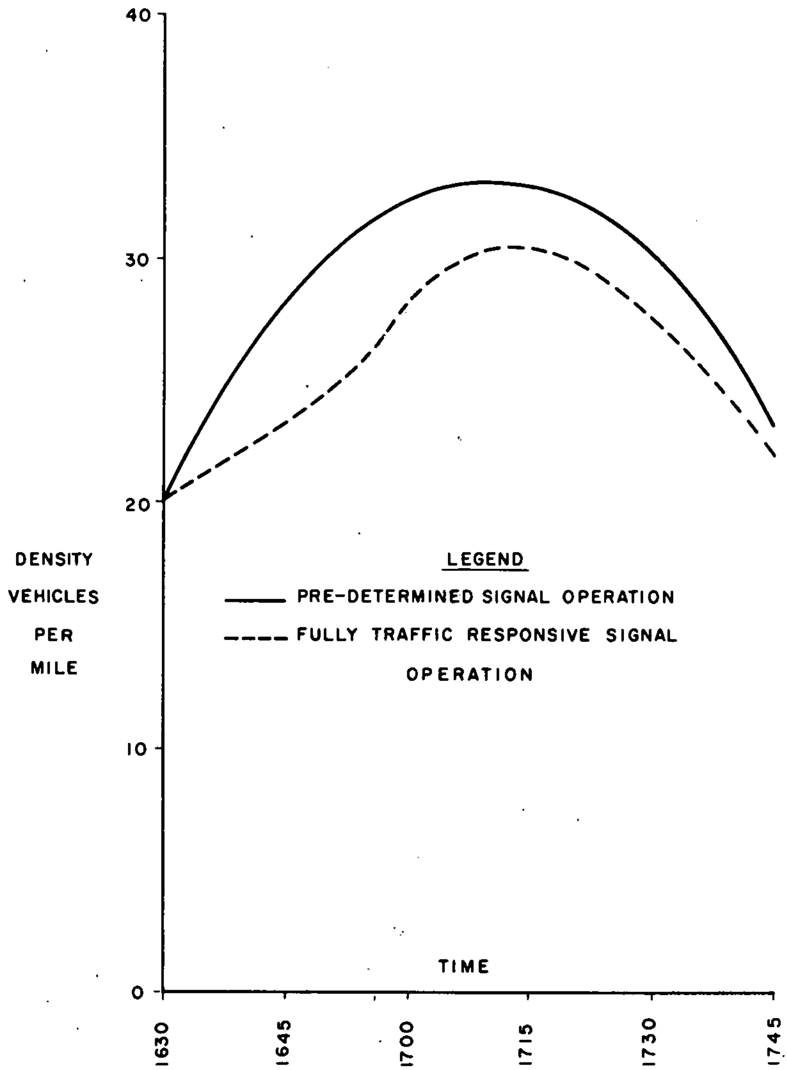

Figure 4. Comparison between the effect of predetermined and fully traffic-responsive signal operation as shown by the measurement of average approach density at a single intersection.

computer record tape, at a single intersection compares conditions when the timing plans are free to select pre-rush-hour and post-rush-hour plans, as well as a peak and rush-hour plan, as against conditions when a restraint is applied to prevent any change except from moderate traffic to peak traffic. The selection of the pre-rush-hour plan prevents a build-up of traffic density. This advantage is maintained throughout the peak period. The post-rush-hour plan assists in shortening the total duration of the heavy traffic period.

VOLUME-LANE OCCUPANCY RELATIONSHIP

At the present time, it is necessary to relate speed and traffic volume in order to avoid misleading interpretation of detector data by the traffic signal control program. For

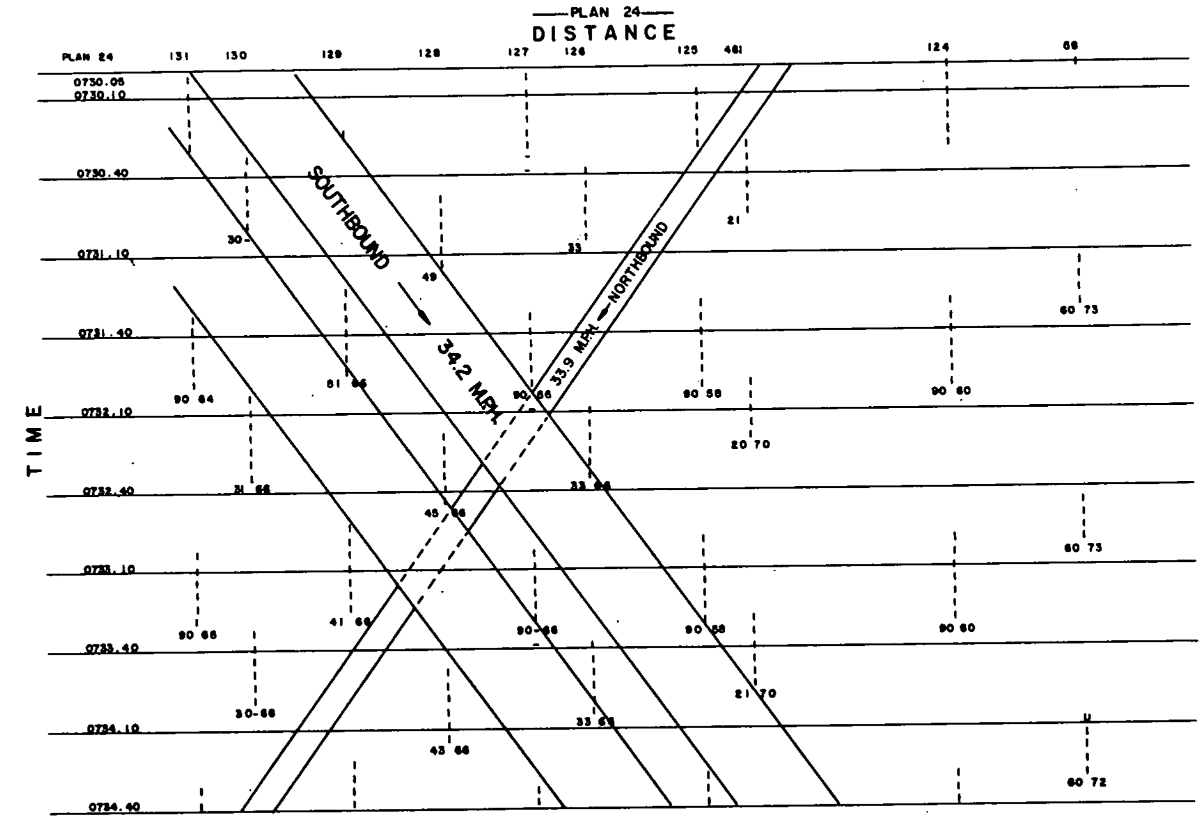

Figure 5. Computer-derived space-time chart showing correct peak-hour signal operation on an urban arterial street.

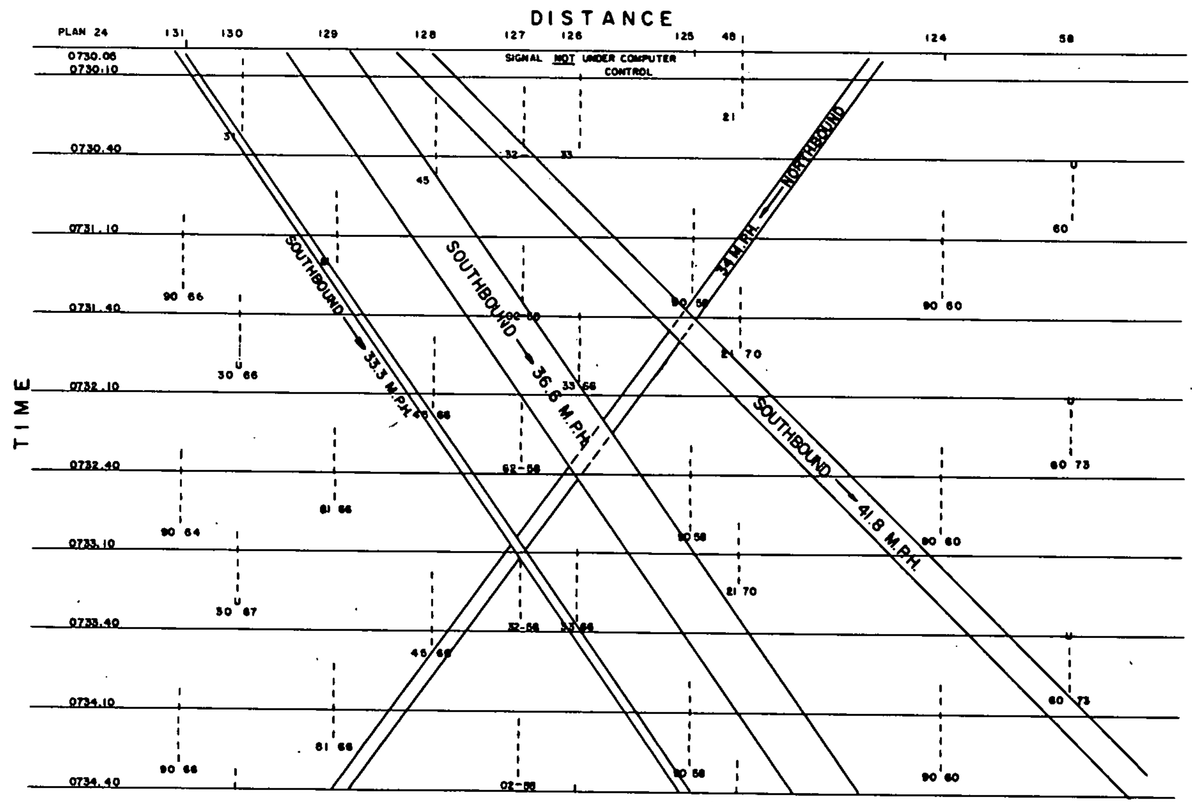

Figure 6. Computer-derived space-time chart showing the effect produced by a signal not under computer control during the peak hour on an urban arterial street.

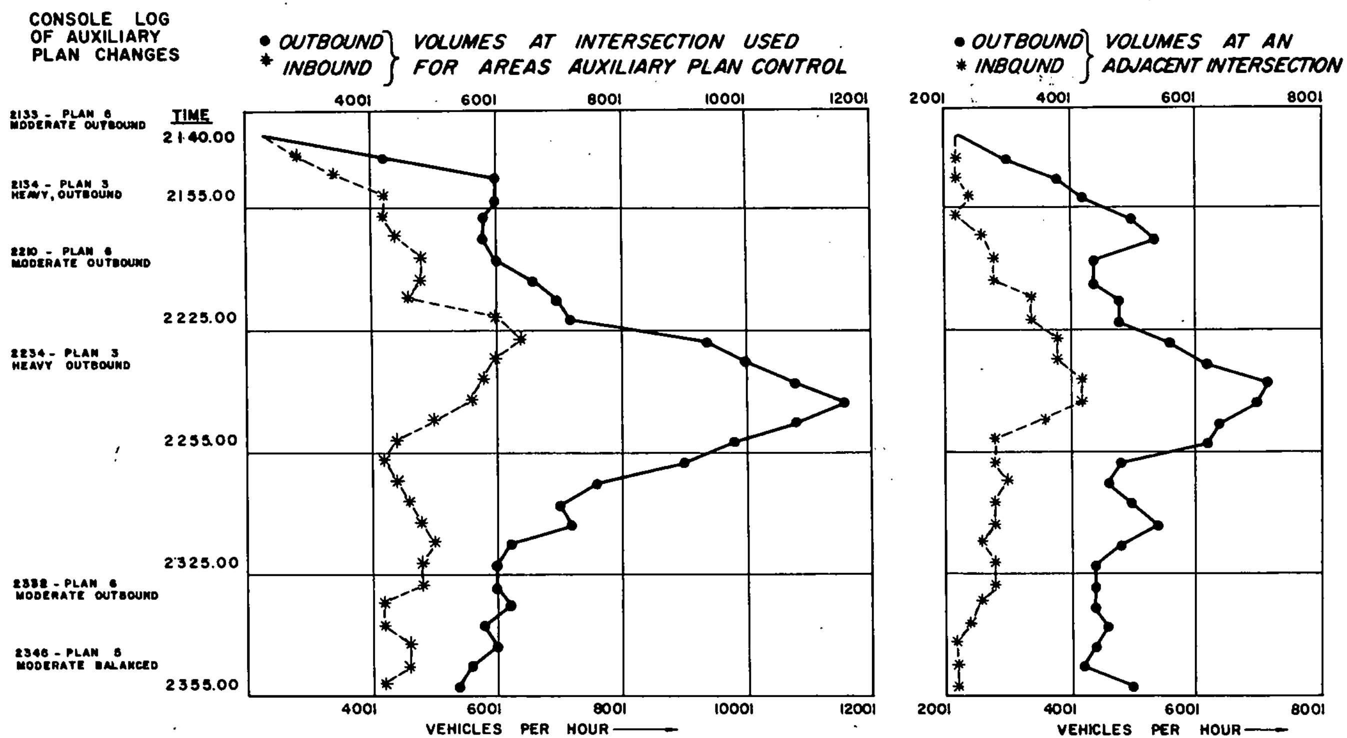

Figure 7. Computer-derived operation plan change points related to traffic demand.

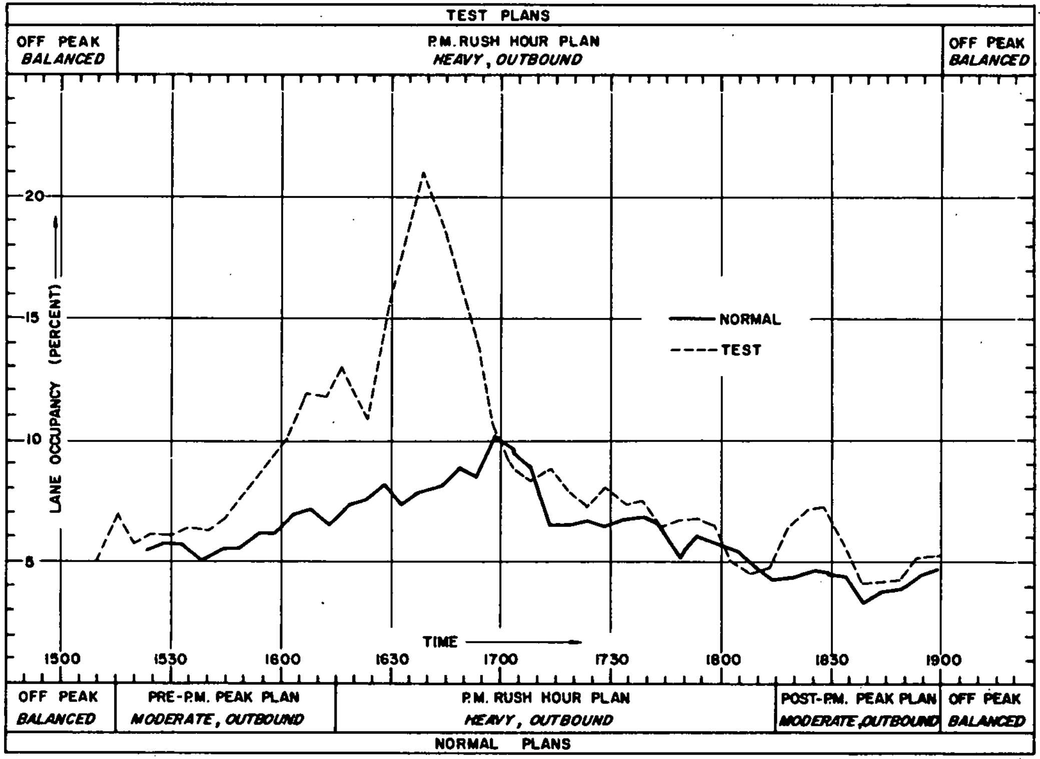

Figure 8. Effect of a plan change malfunction on peak-hour intensity at a point on an urban arterial street.

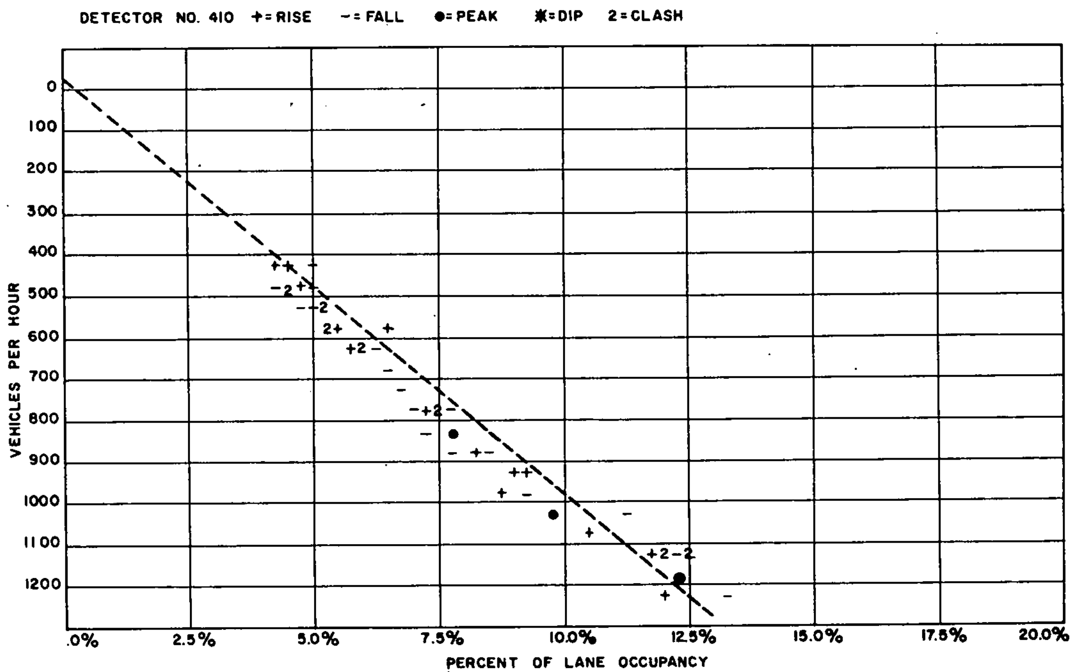

Figure 9. Computer-derived volume-lane occupancy relationship for free flowing traffic.

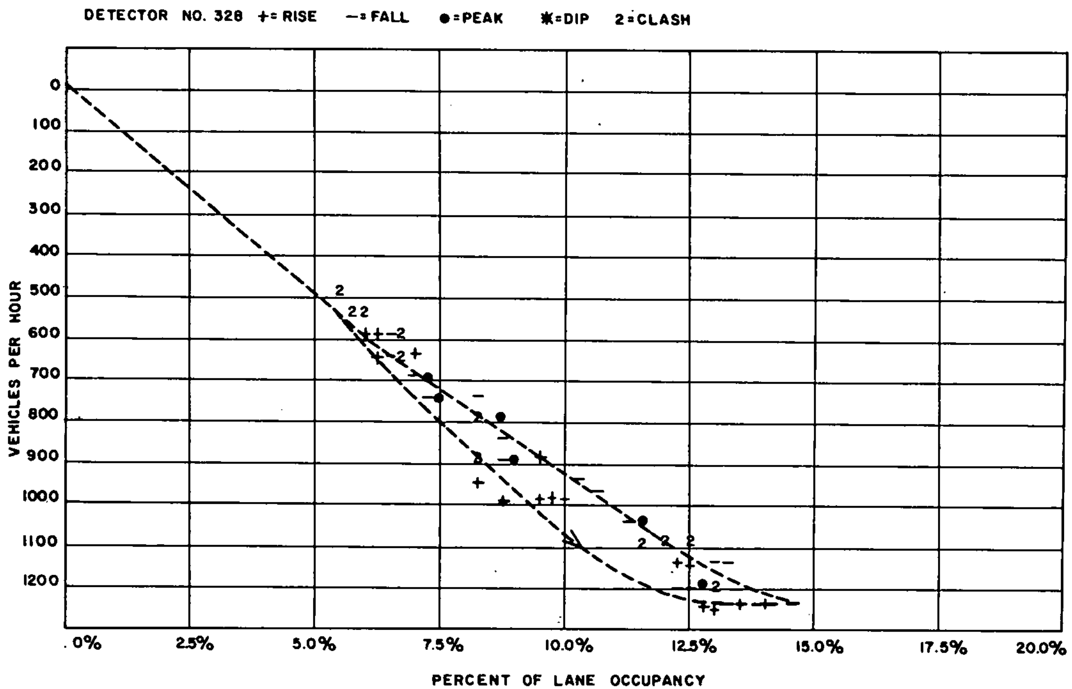

Figure 10. Computer-derived volume-lane occupancy relationship for traffic on a signalized intersection approach.

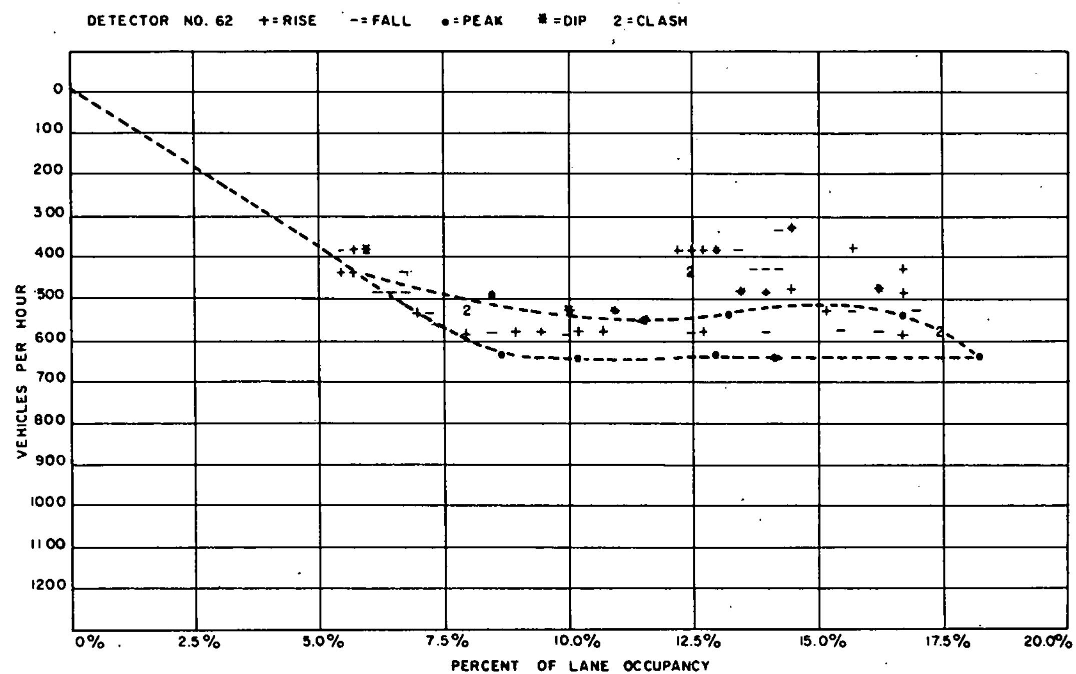

Figure 11. Computer-derived volume-lane occupancy relationship for congested traffic.

Figure 12. Metropolitan Toronto traffic control computer center.

example, a low volume might represent very little traffic, or very congested traffic. To interpret this volume count, the speed (as represented by pulse length) must be ascertained. Thus a low volume at free-flow speeds means there are few vehicles, whereas low volume at very low speed means congested conditions. The possibility has been examined for replacing the two parameters which are presently used, with a single representative parameter. Such a parameter might be lane occupancy as measured by the ratio of pulse length to total time. In an attempt to examine relationships of volume and lane occupancy, computer printouts were obtained for a number of locations having differing degrees of congestion. Figure 9 shows the relationship at an intersection where traffic was relatively uncongested even at high volumes. The relationship appears linear.

Figure 10 shows the relationship when some congestion was noted at high volumes. As the volumes reduced, the lane occupancy curve did not return along the same line, but formed what might be termed a "hysteresis loop." Figure 11 shows conditions at an intersection which was congested throughout the period of study. It would appear that the relationship is similar to the hysteresis loop in Figure 10. Much study is still required before lane occupancy can be reliably used as a single parameter to trigger timing plan changes. Figure 12 shows the computer center.

CONCLUSIONS

There are distinct advantages to be derived from signal network operation, however, the timing plans and coordination plans require careful designing. The extent to which improvements may be obtained is difficult to predetermine. This indicates the need for more research of an empirical nature, using actual systems, to determine simpler and surer methods of designing optimum timing and coordination plans, and methods of evaluation to permit a predetermination of the extent to which improvement is possible.

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