Automatic traffic signal control systems—the metropolitan Toronto experience

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INTRODUCTION

Like a number of fast growing North American cities, Metropolitan Toronto is faced with the ever increasing problems of greater motor vehicle traffic volume, congestion and accidents. Metropolitan Toronto today has more than 700,000 vehicles registered in its 240 square miles, for a per capita density that rates behind only Los Angeles. In addition over 100,000 vehicles from outside the area converge daily on the City.

In 1957, Mr. S. Cass, Metro's Commissioner of Roads and Traffic, along with a consulting firm began to explore the methods open to them to improve existing roads and streets and, in so doing, gaining greater traffic throughput per dollar in comparison with the building of expensive, new main arteries. The concept of computer controlled traffic signals to co-ordinate and thus improve traffic movement seemed to be an answer, providing it was feasible.

Their preliminary investigations indicated that if a general purpose computer were operated in real-time and on-line, it could:

1. Take in traffic information from a large number of vehicle detectors, determine the interval length required at each individual intersection, and optimize these for overall system efficiency considering existing conditions.

2. Determine the optimum time relationship or offset between individual intersection, considering the existing traffic speed and direction of flow.

3. Directly control the individual signals to produce optimum conditions.

4. Check the signal operation and resulting traffic movement to ensure that conditions were optimum.

It was further shown that a real-time computer could alleviate many of the restrictions and problems confronted in using the normal electro-mechanical or more specialized analog equipment to control signals. A computerized traffic signal control system would allow for:

1. Flexibility in changing certain signal phase arrangements and concepts by only changing the computer programs and not the signal equipment.

2. Co-ordination of data between a variety of types and makes of signal equipment and vehicle detectors.

3. Having a variety of operational plans available and implementable in very short periods of time.

4. Collecting current, complete and accurate traffic flow information from all system signals for use in determining system performance, reliability, and optimum traffic control plans.
The computer based traffic control system concept was seen as the best approach to the problem of moving more traffic through Metro Toronto's streets in less time, but some doubts were still raised as to its operational feasibility. So, in the summer of 1959, the Metropolitan Traffic Department began a pilot test of an Automatic Traffic Signal System. Nine traffic signals along 1.7 miles of one of Toronto's busiest streets were linked to a computer and automatically controlled until the Spring of 1961. A comparison of this automatic system with the usual time-cycle control of traffic lights produced these results: in the evening rush hours, computer control reduced the average delay per vehicle by 11 percent; in the morning rush hour by 28 percent; and it reduced congestion by 25 percent. These dramatic results were achieved with a very limited test system and gave credence to the concept of computer controlled traffic signal systems.

In 1961 the Metropolitan Council decided to go ahead with the installation of a Metro-wide automatic traffic signal control system. At that juncture, a time phased implementation program was begun. By the end of 1969, some 850 intersections will be under computer direction. As of February 10, 1969, 594 traffic signals are under the control of a UNIVAC 1107-UNIVAC 418 computer system.

The most important factor in the Metro Toronto system and the one that makes it the most flexible yet attempted, is that every Metro street with signalized intersections is to have sensors reporting to a central computer. Computer decisions are based on traffic situations at different levels. Certain decisions are made at the individual intersection level without regard to anything else. Other decisions are made at the control area level (15 signals), the group level (6-7 control areas) or the system level (5-6 groups). The computer can detect and analyze major traffic movements and make traffic signal adjustments to prevent potential congestion.

As the installation of the system progressed, theories were put into practice; some worked and others fell by the wayside. Through trial and error, two basic modes of control have emerged as practical methods for the system. Due to the flexibility of the system, the computer is able to implement control gradually across the City and combine a simple mode with a more sophisticated and ultimate mode of control.

At the present time there are several different levels of sophistication. Many areas of the City are entirely pre-programmed with all changes in signal timing initiated by time of day or manual intervention. Many other areas have traffic responsive control at critical intersections (TR2 mode) but have area strategy changing by time of day. A few areas have traffic responsive control (TR2) at critical intersections and traffic responsive area control. One area has all intersections traffic responsive and complete traffic responsive area control.

The traffic control system dynamically senses traffic from detectors strategically placed at each intersection. Acting like an inductance loop, they detect the presence of a metal mass and transmit signals to the central computer site via telephone lines. The computer complex consists of a UNIVAC 418 Real-Time Computer that acts as a communications and message switching device interfaced to a UNIVAC 1107 thin-film memory computer and its peripheral equipment. The 418 has controlled 500 signals in a fixed time mode without the 1107.

The actual traffic count is maintained by the computer. By the use of audio tones, signals are sent over telephone lines connected to a Multiplexer at the central site. Through it, the signals are distributed to their correct address in the Input Scanner, which, in turn, is looked at several times per second by the UNIVAC 418. Thus, a detection followed by the absence of a vehicle presence is one car count to be stored in the computer memory. After some data reduction in the 418, the information is transmitted to the 1107, which determines the optimum traffic light pattern for the City and returns the information to the 418.

From there, the information goes to the Output Distributor. The Distributor contains electrical relays that relate to specific signal locations, which open or close in response to the 418. Thereby each unique traffic control box at an intersection can be addressed by the 418 computer.

Monitors in the traffic control boxes provide data to the 418 computer to confirm that the controller responded correctly to instructions. Should any part (or all) of the system malfunction, the computer will relinquish control of the signals effected to local phase timers in the traffic control boxes. To provide complete protections, the 418 must report constantly via a hold relay to each controller; otherwise, the controller will automatically take over on a pre-set time cycle. The complete cycle of examining the traffic situation throughout Metro Toronto, and taking action if required, is performed once every second. At the same time, the 1107 stores data for future analysis and runs other programs concurrently. The benefits derived from such a control system are numerous:

1. The optimization of traffic control signals has
greater throughput and fewer involuntary steps.

2. Flexibility of control allows the system to be tailored to specific areas and situations within the whole system.

3. Manual control of signals by police is reduced, permitting better allocation of police manpower.

4. Accidents and abnormal traffic congestion are sensed and correction methods automatically implemented where possible.

5. Millions of dollars worth of wasted citizens' time and capital equipment can be saved.

6. Reduction in accidents due to better control can save citizens an estimated $1.5 million dollars annually, not including doctors' fees, lost time, lawyers' fees and court awards.

### Secondary computer complex

The secondary computer, which acts as the on-line input-output device for the 1107 to which it is coupled through a special inter-computer synchronizer, is a modified UNIVAC 418 having:

1. A ferrite core memory for 16,384 words of 18 bits each which can be modified to give 8,192 words of 36 bits. In each case, the access time is four microseconds.

2. Input-output capability over eight channels for 18 bit, or four channels for 36 bit words.

3. Control console featuring a ten-character per second buffered type printer and entry keyboard.

4. Input-output facilities using punched paper tape, operating at a rate of 200 input or 110 output characters per second in six columns.

### Operation

The basic function of the computer is to inspect each individual signal once per second and to determine if its aspect should be changed. This is done by comparing the elapsed time for the current indication with that time considered necessary to satisfy both the needs of the alternating traffic flows and the system as a whole.

### Control plan

To provide for predictable variations in the requirements (both at and between individual signals) and to facilitate the implementation of special arrangements (such as flashing operation) many different control plans are available. They are maintained either in memory or on drum depending on their frequency of use. The plan actually in effect at any time may be changed either manually by console type-in or automatically by time of day and/or volume criteria.
which is continuously up-dated to show in one second increments for each intersection or vehicle detector:

1. The elapsed time for the current interval.
2. The presence or absence of a vehicle on a secondary detection.
3. The occurrence of a pedestrian push button actuation.
4. The number and duration, in 32nd of a second, of the pulses coming from each primary detection.

The 1107 processes the raw data to give traffic volume, speed and density over sampling periods of any desired length. By using appropriate input parameters, estimates of delay, congestion, etc., can also be arrived at; thus, a very complete picture of current traffic conditions can be obtained.

Signal control

The control procedure governing the operation of any signal and repeated continuously at intervals of approximately one second, is as follows:

1. Read-in the Signal Monitor Code.
2. Identify the current interval and note the time for which it has remained unchanged.
3. Check to ensure that the monitor code is valid.
4. If not valid, repeat check in three successive scans. If still not valid, the signal will be dropped from computer control and the operator notified by console print-out that this action has been taken.
5. If the code is valid, check whether or not any pre-emption is allowed or necessary. If so, set the special function selector and terminate the interval.
6. If no pre-emption is required, determine whether the interval may be extended.
7. Determine the required interval length.
8. Issue the change order when the computed and elapsed time equate.

Interval length

For a pre-determined mode of operation, the exact length of all intervals will be specified in the parameter list. However, for traffic responsive operation, only minimum values will be given for those intervals whose duration may vary. The need for extension beyond these minimum values is determined by a special computer sub-routine. A great many different time determination procedures may be used. These may be either for different signals, for the same signal at different times of the day, or for different traffic conditions. For any signal, the actual procedure to be used at any instant will be specified by the control plan in effect. In the general case, variations are only required in the length of the normal green time. But, in certain instances, the advanced green time may also be made responsive to traffic demand.

Where all signals operate independent of each other, the length of the normal green indications can be calculated in any way desired including predetermined, semi-and fully-actuated and fully traffic-responsive. There are very few signals of this nature in Metropolitan Toronto.

Where the operation of signals on a given street or in an area must be co-ordinated to permit progressive movement, the determination of interval lengths must be made in accordance with modified routines designed to accept the limits imposed by the required cycle and offset relationship.

Pickup and dropout

With the computer correctly loaded with appropriate programs, a manual type-in at the 1107 console engages the pickup routine which automatically brings the selected signals under computer control. If the field equipment does not respond to the pickup instructions, a fail message will be printed out and further attempts at activation are made by direct manual instruction from the operator.

Pickup occurs at each intersection as its timing dial reaches the appropriate point. The whole system can be under control in little more than two local cycles which is never more than about three minutes.

A manual type-in terminates system control of signals. A dropout routine is actuated and adjusts the offsets of each group of related signals to a good off-peak compromise which can then be provided by the local timing dial. When the correct relationship has been established, the timing dial is started by the computer and operation continues without interruption. Following dropout, the operation of each signal is monitored for approximately five minutes and any deviation from normal is indicated by a console print-out.

Accomplished in this way, dropout may take up to fifteen minutes to complete, but the signals will hold in the correct relationship for weeks if necessary.

Analysis

The computer can carry out a series of analytic functions on a pre-determined schedule or on demand. These include both on-line and off-line analysis.
On-line analysis

Aspect changes at any one signal or vehicular movement past any one detector can be displayed on the 418 console as they occur. This provides useful information for service personnel engaged in checking equipment. Aspect information is available even when the system is not under computer control.

A RECORD routine analyzes and prints out information from any four signals together with any sixteen detectors to show, at one second intervals, actual clock time, signal aspect, the number of vehicles passed during the previous second, length of the pulse produced by the last vehicle, and the existence of congestion for each approach.

A SENSOR routine is designed primarily for testing the acceptability of detector information. Results are printed out at fifteen minute intervals to provide an immediate record of traffic conditions and an indication of the need for servicing.

Off-line analysis

Various routines are available for off-line analysis of information stored on magnetic tape. These routines can perform the following functions:

1. Print volumes, average pulse lengths, and lane occupancy for individual detectors, or groups of detectors, for any time interval from one second to several hours, and for any combination of days. The information can be presented in numerical or graphical form.
2. Produce summaries of actual aspect timing on a second by second, cycle by cycle or hourly basis.
3. Draw space - time charts of co-ordinated arteries on a second by second basis.
4. Simulate delays, stops, queue length, etc., for one intersection based on the real vehicular input and actual signal aspects.
5. Calculate congestion for up to 200 approaches individually and as a group.
6. Produce graphs of delay for a variety of offsets and graphs of stops for a variety of offsets, based on an average platoon arrival distribution that is calculated from recorded data. The computer also produces a figure of merit which estimates the importance of co-ordinating a particular link.
7. Produce volume figures which are corrected for double lane counting losses so that computer produced volumes are within ±10 percent of actual volumes.

After four or five months have elapsed, the detector information contained on the original data tape on a second by second basis is averaged over 15 minute intervals, to provide for long-term data storage and more convenient preparation of weekly, monthly or yearly comparisons. One tape can hold a year of data in this way. This compressed data tape may be analyzed at any time to provide any required information except that concerning signal aspect. The original data tape is normally cleared and re-used after six months, unless some Court action is pending.

Performance

Area control

On almost every street there is, at some point, a natural discontinuity for through traffic. On the other hand, there are many areas in which signals are so closely spaced or traffic conditions are so similar that close co-ordination and a more or less identical mode of operation is mandatory. Combining these two factors, some sixty so-called Control Areas, each of which can be considered as more or less independent unit, have been created. Signals in these Control Areas can be operated in any required way without reference to conditions in adjacent areas. Many of these Control Areas include signals in network formation, only those on a single street, or those on a section of a major arterial route.

The Control Area concept has simplified programming, data handling and evaluation, while increasing operational flexibility. Insofar as is practicable, both the initial connection of signals into the system and all future development work is carried out on a Control Area basis.

Route control

To provide a thorough check on equipment and a later basis for comparison, the initial operation of each group of signals on a common street has been in a strict pre-timed progressive mode, using plans prepared by the computer. A comparison between this mode of operation and the previous non-coordinated arrangement shows a very distinct improvement. Over a large area, travel time and the number of involuntary stops decreased by an average of some eleven and forty-five percent respectively. The average speed and number of vehicles passing in a given time increased by some thirteen and ten percent respectively.

During the next stage of development, the same predetermined plans were used. However, critical intersections were put in the TR2 traffic responsive control mode and area control parameters were selected on a
volume basis as well as a time of day basis. The thinking here is that any feedback control system must have an inherent lag in response time in order to be stable. Secondly, the time scale on which area control parameters are determined and implemented is quite large. Thirdly, providing the appropriate area strategy, for say the peak of the morning rush hour, creates small problems if done too soon and creates large problems if done too late.

Therefore, if the traffic responsive mechanism has not initiated a particular rush hour plan by a certain time, then that plan will automatically be implemented by time of day.

This type of traffic responsive operation proved quite successful in that the duration of peak hour congestion was considerably reduced, though it was not eliminated, while the increased flexibility allowed the system to automatically adjust for the variations in traffic demand resulting from holidays, sporting events, etc.

In periods of light traffic, one of the major problems lay in the close spacing of many minor signalized intersections which prevented two-way progressive movement at any reasonable speed. To overcome this problem, secondary detectors have been installed and a number of these intersections operated in a semi-traffic responsive mode. Their yield point has been determined by the through street requirements and the minor street use times. Another method used is to have several minor signals operated in a flashing mode, with red presented to the side street and amber to the major. One hundred and fifty signals currently operate in such a way at certain times of the evening.

**Critical intersection control**

**TR2 control**

To overcome uneven traffic flow at critical intersections, the proportion of green time allotted to either phase can vary almost directly with instantaneous demand, while retaining a fixed cycle length. It was found that during peak periods the average delay per vehicle could be reduced by some twenty-seven percent.

**TR1 control**

A very few major arterial intersections are sufficiently isolated that they cannot be considered as part of a progressive system on either street. In these cases best results have been obtained using an improved volume density type of control. In these instances both cycle length and split vary in accordance with the almost instantaneous demand. With this type of operation, it has been possible to reduce the average delay per vehicle to about thirty seconds, or ten percent, while handling a peak volume equivalent to some fourteen hundred vehicles per lane, per hour of green.

With both these modes of control, it has been found that serious trouble could develop if volume alone, or volume and density alone, were used as the basis for split variation. If, for any reason, congestion developed on one approach and not on the others, in a given sampling period the detectors might indicate that the street on which free flow was taking place was carrying the larger volume and hence it would be given the larger share of green time. This process could be cumulative until the congested street is actually receiving its minimum allowable green in spite of its urgent need for more time. To overcome this, a congestion identification routine is used. This routine detects congestion by analyzing pulse lengths and volumes. The routine provides compensation by artificially increasing the count on the affected street, for TR2, and by ensuring a large minimum green time for TR1.

**Turning movement control**

At a great many intersections where turning movements present a problem but are not sufficient to warrant a completely separate phase, conditions have been greatly improved by using a split phase arrangement. In this arrangement the green for one direction comes on in advance of that for the other. During this usually short interval, the green for the favoured direction is caused to flash rapidly, this alerts the drivers to its presence and duration while, at the same time, allowing the feature to be omitted at any time without the need for special signs. To provide for clearance and increased safety, the flashing green is changed to a steady indication for about two seconds before the opposing direction is allowed to move.

It is hoped that this selection can shortly be made in accordance with traffic demand at least at those intersections where separate turning lanes are provided and detectors can be located to record the movement.

**Accident control**

A comparison was made of Police statistics for two similar downtown sections of the City, each approximately two square miles in area with some ninety signalized intersections. It was shown that in one where no change was made in signal operation, traffic accidents increased by five and one-half percent over a two year period, while in the system where control was introduced, there was an accident decrease of about seven and one-half percent. A comparison of conditions on three major arteries has shown that accidents have
decreased by some sixteen percent although the volume of traffic has increased by some twelve percent.

**Snow plans**

It has been found that during even light snow, control efficiency drops sharply simply because of the time required to start a vehicle on slippery pavement. (This is especially true for any approaches on inclines.) On the theory that once movement has started it should be allowed to continue for as long as is reasonable, special plans have been designed to provide considerably longer than normal signal intervals. Longer ambers are also used with these plans.

**Economic benefits**

Given the amount of accident reduction that the computerized traffic control system has produced (some 10 to 15 percent), it can be safely projected that the system should be saving the citizens of Toronto and its environs some 1½ million dollars annually. This is based on the fact that property damage from auto accidents in Toronto runs to well over 15 million dollars annually. The savings from the increase in traffic flow has been estimated at about 18 million dollars per annum, based just on vehicle operating costs. If the personal time saved could be estimated in dollars, this figure would increase dramatically. Thus, we have a community savings of some 20 million dollars per year on a capital outlay of only five million dollars for the total system.

When the computer was moved recently from the old City Hall to the new Police Headquarters, Toronto residents found themselves caught up in a three-week traffic jam since the lights were on their own automatic controls. Motorists were warned of the move and cautioned to leave for work earlier than usual. Once the Computer System, that has reduced traffic tie-ups by 20 percent was no longer controlling the traffic lights, motorists found that in some cases they needed up to an extra hour to get to work. The earlier system predictions of the saving of some 9,000 vehicles hours of delay per day proved to be a gross understatement during those hectic weeks.

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