Stability of Occupancy-Based Library Traffic Control Systems

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The purpose of this paper is to investigate the long-term behavior of a class of closed-loop (feedback) traffic control systems that select an appropriate program from a prestored library on the basis of occupancy information. The subject of traffic control system instability is defined and expounded on. The effects of various factors on traffic control system behavior in general and on stability in particular are explored. Among the factors whose effects are scrutinized are sensor placement, degree of parameter smoothing (system damping), degree of directionality of the control-program library, and the value of threshold and hysteresis used for program selection. Sensor placement in locations sensitive to the formation of queues that require system reaction is advocated in combination with a threshold level composed in its entirety of a hysteresis band. Such a band is shown to provide a good match between traffic conditions and programs handling them and is also shown to reduce or eliminate unstable behavior under certain conditions. The results summarized in this paper were derived from simulating a closed-loop traffic control system operating on a four-intersection corridor. More than 600 simulation runs, each 1 h long (real time), were conducted for various combinations of parameter values. Aggregate delay is used as the measure of effectiveness for comparing these parameter-combination sets.

Recent developments in traffic signal control algorithms have resulted in little demonstrable improvement to measurable parameters of traffic flow quality when compared to older, trustworthy algorithms mainly because the vast majority of research to date consists of the construction and implementation of traffic control programs (set of signal parameters designed to handle a particular static traffic condition) rather than the design of traffic control algorithms (prescribing the control system's behavior for any set of time-varying traffic conditions). More recent work has involved new generations of signal control systems that, by design, use control algorithms within which control programs do not exist as precalculated entities. The lack of success (1, 2) of these algorithms (which should achieve better results than older control systems) is partially attributable to the lack of clear understanding of the behavior of closed-loop traffic controllers. These are controllers that use field sensor data to generate a set of control parameters implemented at the signals being supervised by the system.

This paper is dedicated to the investigation (through simulation) of the long-term (1-h) behavior of a closed-loop traffic control system. This system has a control algorithm that switches among a precalculated set of control programs according to the value of a decision variable calculated from field sensor outputs. The decision variable used here is occupancy (percentage of time a field sensor is covered by vehicles). The simulations are limited to systems that use fixed-time (open-loop) intersection controllers, but similar results are expected for other cases, such as systems with semiactuated intersection controllers. Two different transition algorithms are studied for smooth shifting from one offset program to another when the main algorithm calls for such a change.

Occupancy is extensively used on contemporary traffic control systems. Because this variable is affected both by the control programs implemented and by prevailing traffic conditions, to expect occupancy-based switching to result in control-system instability under a wide range of conditions is reasonable. Simulation studies demonstrated these anticipated oscillations.

Although this paper should yield a firmer basis for the understanding of the behavior of closed-loop traffic control systems and for the design of new generations of control algorithms, parallel studies of volume-plus-occupancy-controlled algorithms are in progress. Qualitatively similar results are expected from those simulations when a significant weight is assigned to occupancy.

TEST CORRIDOR

The corridor selected for demonstrating the long-range closed-loop behavior of the occupancy-based traffic control system consists of the portion of Ashburton Avenue in Yonkers, New York (population 205 000) shown in Figure 1. In Figure 1, arrival rates are in vehicles per hour. Ten percent of the main arrival streams turn away onto the first side street (Nepperhan or Park avenues) in each direction. Side arrival rates refer only to vehicles turning onto Ashburton Avenue (50 percent in each direction). Twenty percent of the main-line flow turn away from Ashburton Avenue at each intersection except at the first intersection. The arrival rates used for most of the simulations depicting unequal flow are 840 vehicles/h in one direction and 540 vehicles/h in the other. The notation used is 540/840. Figure 1 shows equal arrivals of 840/840. Side arrival flows from both directions of each side street were combined for simplicity and are represented in Figure 1 as a T-intersection. One lane of moving traffic in each direction exists on the corridor and on each side street.

CONTROL ALGORITHM

Fixed library control algorithms are examined here. These control algorithms are defined as first generation control software in Urban Traffic Control System (UTCS) terms (3). The selection was made because the vast majority of systems used to date use similar algorithms. Such algorithms consist of a policy that switches among specific, precalculated control programs (the library) in an attempt to fit each implemented program to a set of modified sensor measurements of traffic parameters (such as volume, occupancy, or some combination of the two). Occupancy has been selected as the decision variable in the system investigated here.

Discussion is limited to the corridor previously described with one sensor placed in each direction between St. Joseph and Vineyard avenues. This corridor section, which consists of 4 intersections, was considered small enough so that one sensor in each direction would suffice. The sensors are placed on an internal link of the corridor to reduce the effects of the vehicular arrival process (from outside the study area) on arrivals to the sensed link (modified here by two signals) and because the location is central in the corridor and, unlike an off-central location, has a larger chance of faithfully representing conditions throughout the corridor. The control algorithm used a three-program library made up of:

1. A program favoring one direction of travel,
2. A program favoring both directions equally, and
3. A program favoring the second direction of travel.

Most existing algorithms have the added option of permitting selection of a cycle length; this dimension was not examined in this study. The programs stored in the library are based on offset relationships, the cycle length is fixed at 60 s, and all signal splits are constant.

Three different three-program libraries are considered:

1. Slightly directional with a green-band ratio of 45 to 35 percent of the cycle,
2. Moderately directional with a green-band ratio of 55 to 25 percent of the cycle, and
3. Superdirectional with a green-band ratio of 63 to 17 percent of the cycle.

The program handling average of conditions is common to all three directional-intensity program sets and has a green-band ratio of 40 to 40 percent of the cycle. The directional programs favoring the second direction are symmetric to the ones favoring the first direction. The programs could have been calculated subject to any criterion, but an attempt was made to use the most widely used method: bandwidth maximization. Some attempt is usually made in practice to match the ratio of the incoming volumes (on the corridor) to the ratio of the directional-program bandwidths. This attempt succeeds in matching the ratios for limited time periods only because arrival rates vary with time. One of the main reasons for implementing a closed-loop control system is the unpredictable nature of arrival-rate changes and their times of occurrence.

The control algorithm selected for this investigation causes program switching to occur according to the size of the difference between the smoothed values of the occupancy decision variable in the two directions of travel; the algorithm will switch from a balanced program to a directional program when the size of that difference exceeds a predetermined threshold. The decision variable S used to determine the need for program switching is devised in two steps. First, at the termination of each control interval (one 60-s cycle in this case), the cumulative sensor output during the past control interval is used to update a running average of the sensed parameter. The updating is done as follows:

$$\overline{X}_{n+1} = (AVP \times \overline{X}_n) + [(1 - AVP) \times X_{n+1}] \quad (1)$$

where

$\overline{X}_n$ = smoothed sensor output after control interval n,
X_{n+1} = cumulative sensor output in control interval n + 1, and
AVP = averaging period value.

The AVP value is a fraction between 0 and 1 that defines the number of intervals at which the smoothed sensor output $\overline{X}_n$ has a certain percentage level effect into the future. The following tabulation gives the number of future control intervals in which a sensor reading accumulated during one cycle contributes at least 10 percent of the total smoothed value:

AVP Value (%)	Duration (s)	AVP Value (%)	Duration (s)
0	1	0.6	5
0.1	2	0.7	7
0.2	2	0.8	11
0.3	2	0.9	22
0.4	3	1	00
0.5	4		

Second, the running average of the sensor outputs in each direction is scaled to represent the percentage of maximal value that this parameter can be expected to reach at oversaturated conditions. For example, if the number of seconds that the northbound sensor is occupied in the nth 60-s control interval is X_n^N, the scaled, smoothed occupancy value will be $y_n^N = 100\ (\overline{X}_n^N/30)$, and program switching will depend on the difference $(y_n^S - y_n^N) = S_n$. This normalization uses 30 s/min as the full-occupancy value, which allows the rare possibility of greater than 100 percent normalized occupancy.

When S exceeds a preset threshold level, a program favoring the direction with the larger smoothed decision variable is instituted. If S does not exceed this threshold level, the average-conditions offset program is used. A hysteresis band is commonly used in control systems with this type of algorithm to prevent program-selection oscillation when the value of S hovers near the threshold level for a period of time. For example, a directional program may be invoked when the threshold level is exceeded by S, but the balanced program is returned to only if S drops below the threshold level minus the hysteresis band (Figure 2). (No program switching is allowed during program transition following a previous threshold passage.)

DEFINITION OF SYSTEM STABILITY

Under certain conditions, a fixed library, closed-loop traffic control system may switch repeatedly among control programs. If such repeated switching takes place under constant vehicular arrival rates at the termini of the controlled street network, the control system might be said to be unstable. More specifically, a traffic signal control system will be defined as unstable if a set of feasible, constant vehicle-arrival rates (one value for each network arrival terminus) into the controlled street network exist that cause the control system to vary its implementation of control programs without settling at the steady-state program most appropriate for that set of constant vehicle-arrival rates. The term "most appropriate" is defined here in terms of the criterion on which the control algorithm is based. This definition of system stability holds for any type of traffic signal control system except ones in which the most appropriate control policy for certain sets of arrival rates consists of oscillation between two or more control programs (4).

EXISTENCE OF SYSTEM INSTABILITY

Control systems that use volume as the decision variable might experience instability when a temporary blockage occurs that affects flow over a sensor location. This instability manifests itself by the selection of a control program that is not the most appropriate for the field conditions. This is the major reason that most manufacturers of signal control equipment avoid the use of volume as the sole decision variable; some manufacturers use a linear combination of volume and occupancy. Such a combination may result in instability similar to that experienced by the occupancy-based system studied here but with a different range of parameters under which such instability occurs.

When occupancy is used as the decision variable and the flow of vehicles into the corridor is such that the difference S between the two directions is below the preset threshold level, the system can be expected to reach a steady state at the average traffic conditions program subject to the influences of other stability-affecting parameters that will be described. When vehicular inputs or other conditions are such that S exceeds the threshold level indicating preferential offset, the system might oscillate in its selection of the control programs without reaching a steady state. This potential instability occurs as follows (Figure 3):

1. The system selects a preferential offset as a result of a threshold passage;
2. The preferential offset helps to reduce S because it reduces occupancy in the preferred direction at the expense of increasing occupancy in the opposite direction; and
3. When S is less than threshold minus hysteresis, the average traffic conditions program is implemented until S exceeds the threshold level once again, and the process is repeated.

BASIC MECHANISMS AFFECTING STABILITY

The basic mechanisms affecting control system stability may be divided into three groups:

1. Traffic-flow conditions,
2. Physical attributes, and
3. Control-algorithm parameters.

The control system designer has little or no control over traffic-flow conditions. One way in which S may rise above the switching threshold is simply by unequal vehicular-input flows. A second way involves the occurrence of a blockage downstream from a sensor location. Such a blockage, when sufficiently close to affect the flow of traffic over the sensor, might start an instability process when the smoothed occupancy in the blocked direction increases sufficiently to cause S to cross the threshold level. A third way involves the occurrence of a blockage upstream from a sensor location; such a blockage can reduce the smoothed-occupancy parameter in the blocked direction sufficiently to push S over the threshold level, favoring flow in the opposite direction.

Most physical attributes are beyond the control of the control system designer. For example, the physical layout of the corridor, the number of lanes in each direction, and the length of the links between intersections are generally fixed. These physical features play a major role in the preparation of the control program library. One major physical attribute controllable by the system designer is the location of the sensors in which data regarding the decision variable originate.

Control-algorithm parameters that are under the control of the system designer and might affect system stability are

1. Averaging period,
2. Threshold level and hysteresis band,
3. Directional intensity of control programs, and
4. Program transition.

SIMULATION PROGRAM

A microscopic program was designed to have the following characteristics:

1. Vehicular-clearance signal phases assumed to be negligible in their effect on system behavior;
2. Initial delay of 4 s before the first vehicle moves at the onset of green with 2-s headways thereafter [3.7 and 2.1 s respectively, based on the numbers given by Greenshields, Schapiro, and Ericksen (5)];
3. Constant headway of 2 s in saturation flow regardless of velocity;
4. Free flow urban velocity of 48 km/h (30 mph); and
5. Shock-wave negative velocity of 24 km/h (15 mph).

The simulation is detailed enough to supply data on vehicular passage over sensor locations so that the proper decision variable values may become available to the control algorithm. This requirement necessitated a microsimulation model in which shock waves are propagated by iteratively tracing individual vehicles through the corridor. The simulation is time based, and individual vehicles are advanced starting at the upstream end of the system during each 1-s simulation interval. The need for long-term observation of closed-loop system behavior dictated an efficient simulation program operating on a street network small enough to yield a high real-to-simulated time ratio. Each simulation run of 3 min corresponds to 1 simulated hour over a two-directional corridor with four signalized intersections (on an IBM 370/135).

The simulation program is a derivative of one described by Longley (6). This simulation differs from that of Longley in the method of tracing vehicles through the network, in the intersection model, and in the sequence of vehicular propagation. Details of the simulation are available elsewhere (7).

Simulation runs conducted to investigate the behavior of the control algorithm acting on unbalanced directional traffic flows were initialized by 20 min of balanced flow before each 60-min run having unbalanced flow. This step type of perturbation to which the system was subjected at the beginning of each run had a twofold purpose:

1. To investigate the effect of such a step type of input on system instability and its duration and
2. To provide information on the quickness of system response to flow changes.

Corridors simulated with balanced arrival flows were initialized in one of the following two methods:

1. The same balanced flow as was provided during the actual simulation period (usually 840/840) with a 4-min preferential control-program perturbation immediately following this initialization period or
2. Unbalanced flow (usually 540/840) for the 20-min duration of initialization followed by the actual 60-min simulation run at the balanced flow (usually 840/840).

Simulations were carried out with both deterministic flows having the indicated rates and stochastic arrivals whose mean rates matched the indicated rates.

SIMULATION RESULTS

Figures 4 and 5 show typical simulation results for the oscillation of S across threshold levels and the corresponding switching among control programs. The following sections present interpretations of these results.

Smoothing

Insufficient smoothing of the decision variable is a major cause of control system instability. Figure 4 shows the behavior of an insufficiently smoothed (AVP = 0.4) system under constant, equal, regular (nonstochastic) saturated arrival rates (1000 vehicles/h in each direction). Note that this simulated system, with splits of 63 percent at each intersection (excluding start-up delay), carries its maximal load (at corridor termini) at about 1000 vehicles/h. Figure 5 shows a sufficiently smoothed (damped) system behavior under the same saturated conditions at a larger AVP value of 0.6. It would seem that, for saturated conditions at the given system parameters, an AVP value of at least 0.6 is called for to prevent unwanted (in this case) control-program oscillations. Results in this case indicate that aggregate delay is reduced when the algorithm parameters are adjusted to eliminate oscillations.

The simulation of systems with stochastic arrivals (in this case with an average of 800 vehicles/h in each direction) yielded the same general results. The system stabilized with an appropriate AVP value usually slightly higher than the one sufficient to stabilize an equivalent deterministically generated arrivals system with the same arrival rates (balanced).

At unbalanced vehicular arrival rates, instability may occur subject to threshold, smoothing parameter, directional flow difference, and the like. Where a system is shown to be unstable for a particular set of unbalanced arrival rates, the smoothing parameter AVP has an effect on the period of control system oscillations and, sometimes, on the existence of such oscillations. At arrival rates of 600/1000 (one direction saturated) and an AVP value of 0.5, the average control-program oscillation period is 5 min. As the AVP lengthens to 0.7, the average oscillation period increases to 5.4 min. At the long AVP of 0.9, the average control-program oscillation grows to 7.6 min. Figure 6 summarizes the relationship between average oscillation period and AVP values with stochastic arrivals of 400/840. The oscillation period generally increases with the AVP value and with approach to an infinite period, which indicates that oscillation disappears at high AVP values.

Threshold and Hysteresis

The effect of the threshold level on system behavior and stability varies with the values assigned to the smoothing parameter, sensor location, control-program directional intensity, and size of the hysteresis band modifying that threshold level. In addition, the threshold level strongly influences the measure of effectiveness (aggregate delay) value derived from the simulations. The threshold should be set in a manner that causes control-program transition when the directional program invoked by this action is better equipped to handle the then-current field conditions. Hysteresis may play a minor or a major part in the threshold mechanism and have a strong effect on system oscillations.

Hysteresis as a Minor Threshold Component

It is clear that the smaller the value of threshold used is the larger is the AVP value required to avoid unnecessary oscillations in control-program implementation. For a system simulated with stochastic inputs, statistical variations in S are sufficiently large to require larger stabilizing AVP values than those needed for systems simulated with deterministic inputs. These larger AVP values damp the system to a point where transient response in reaction to a step input change in arrival rates is almost nonexistent. The critical AVP value (selected from the range of 0.1, 0.2, . . . , 1) changes the duration of transient behavior from greater than 60 min to insignificant values for the case of 800/800 stochastic arrival rates. The critical values of AVP for various threshold levels are shown in Figure 7.

Hysteresis as Major Threshold Component

A major role may be assigned to the hysteresis band in order to

1. Cause the system to match the proper program to traffic-flow conditions and keep this program in operation until the need for it disappears and
2. Reduce oscillations to enable operations at a relatively short averaging period for faster system reaction to flow changes.

Both of these goals can be achieved by putting the entire switching-definition burden on the hysteresis band that is set at the full program-switching threshold level. This hysteresis band setting causes program switching away from the balanced program, as usual, at threshold and program switching away from the directional program only when S returns to cross the 0 percent mark. In this manner, the system is allowed to operate at a directional program if that program tends to equalize occupancy in both directions, which is a desirable trait. The previous arrangement of a threshold level with a small hysteresis band ensured system instability if the directional program was sufficiently matched to the traffic flow to equalize occupancy in both directions (Figure 8). The algorithm operating with a large hysteresis band does not abandon the directional program if it is successful in equalizing occupancy in both corridor directions and is effective in terms of lowering aggregate delay as well (Figure 9). Note that this new arrangement enables the system to operate at low damping (short AVP), insuring fast system response without excessive oscillations.

Figure 1. Ashburton Avenue with simulated arrival rates shown.

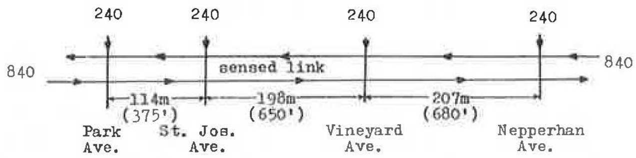


Figure 2. Switching rule.

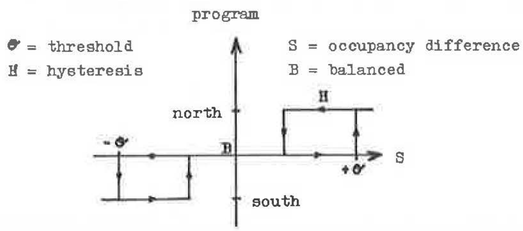


Figure 3. Oscillation at unbalanced flows.

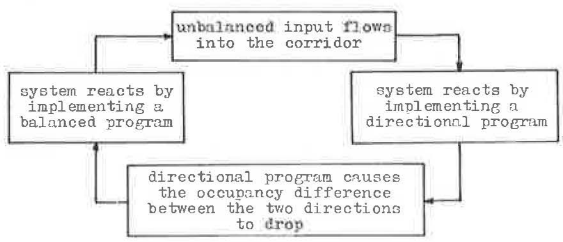
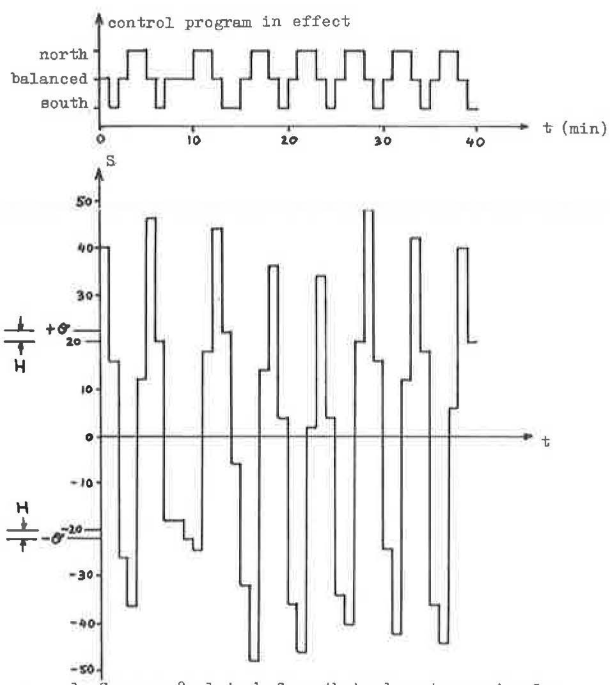
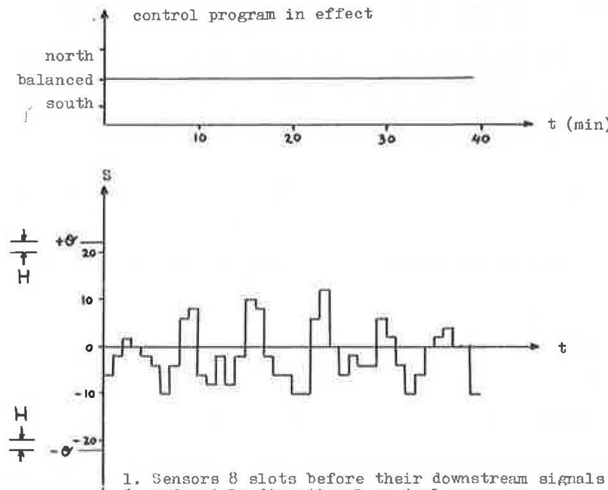


Figure 4. Instability: insufficient damping at balanced, saturated flows for deterministic arrivals.



1. Sensors 8 slots before their downstream signals
2. Moderately-directional control programs
3. Averaging period: AVP = .4
4. Arrival rates: 1000/1000 main, 240 side
5. Initial arrival rates: same
6. Threshold = 22%, hysteresis = 2%
7. Average control-program oscillation period = 7.7 min
8. Aggregate delay = 39,428 veh sec/hour

Figure 5. Stability: sufficient damping at balanced, saturated flows for deterministic arrivals.



1. Sensors 8 slots before their downstream signals
2. Moderately-directional control programs
3. Averaging period: AVP = .6
4. Arrival rates: 1000/1000 main, 240 side
5. Initial arrival rates: same
6. Threshold = 22%, hysteresis = 2%
7. Average control-program oscillation period = ∞
8. Aggregate delay = 31,778 veh sec/hour

Figure 6. Average oscillation period versus AVP.

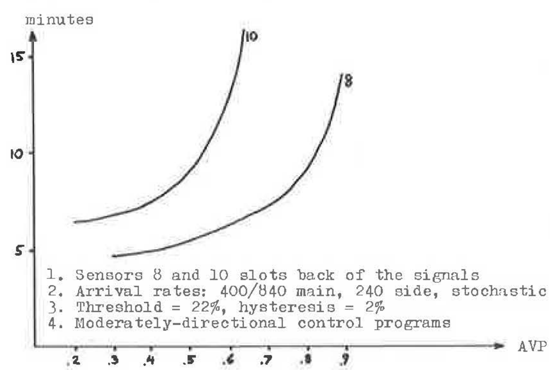
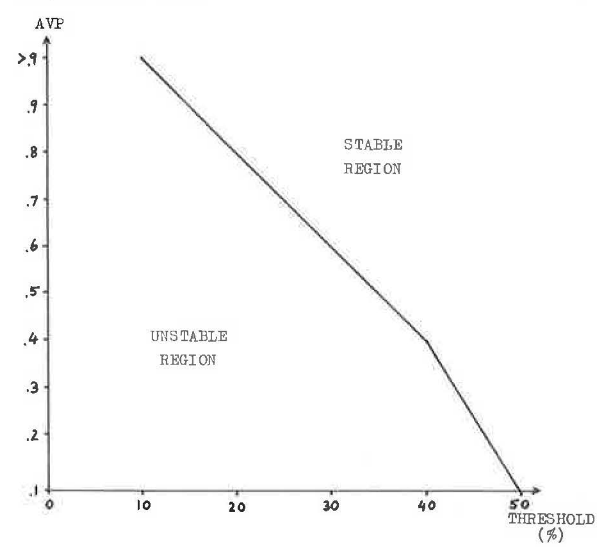


Figure 7. Critical AVP values versus threshold level for stochastic 800/800 arrival rates.



Ideally, each program (balanced or directional) should have a threshold and a band that enable switching away from it in the same manner usually provided for in the balanced program only. Hence switching away from a directional program should not occur at the 0 percent threshold (as used here) but within a "forgiveness" range of a percentage away from 0 percent as in switching away from the balanced program. This feature should be incorporated into future systems; however, this study is addressed to the improvements that can be made in using existing equipment; therefore, the limit to threshold and hysteresis operation was set at a large hysteresis band equal to but not larger than the threshold level.

Control-Program Directional Efficiency

Three control-program sets were compared:

1. The slightly directional program with a green bandwidth ratio of 45 percent/35 percent,
2. The moderately directional program with a green bandwidth ratio of 55 percent/25 percent, and
3. The superdirectional program with a green bandwidth ratio of 63 percent/17 percent.

For each program set, a correlation was perceived for aggregate delay at an AVP value, the number of program transitions, and the suitability of the directional intensity

Figure 8. Usual hysteresis band (2 percent) causes small oscillation period at AVP = 0.4 for stochastic arrivals.

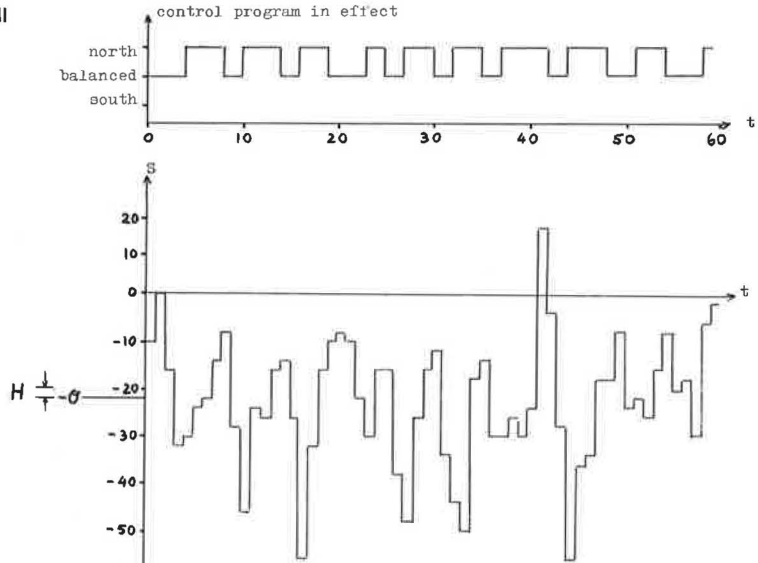
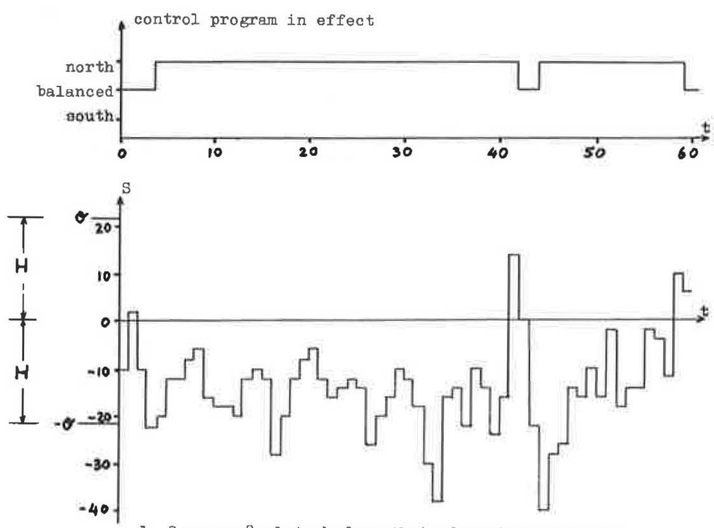


Figure 9. Full hysteresis band (22 percent) enables large oscillation period at AVP = 0.4 for stochastic arrivals.



of the program set to handle the actual flow conditions on the corridor. For example, in general, the fewer program transitions there were, the less the aggregate delay would be. If two different directional intensity program sets exhibit the same rate of program transitions, then the suitability of the directional program influences the delays experienced.

Figure 10 shows the typical behavior of the system through one control-algorithm excursion beyond the threshold in the smoothed-occupancy plane. The axes represent the smoothed value of occupancy (in seconds per minute) in each direction. Successive breakpoints have coordinates (y_n^N, y_n^S). It is interesting to note that the more directional a program set is the faster its points move in this plane and the more nearly orthogonal are its trajectory and the switching lines.

Figure 10. Typical paths in the smoothed-occupancy plane through one excursion into directional-program use.

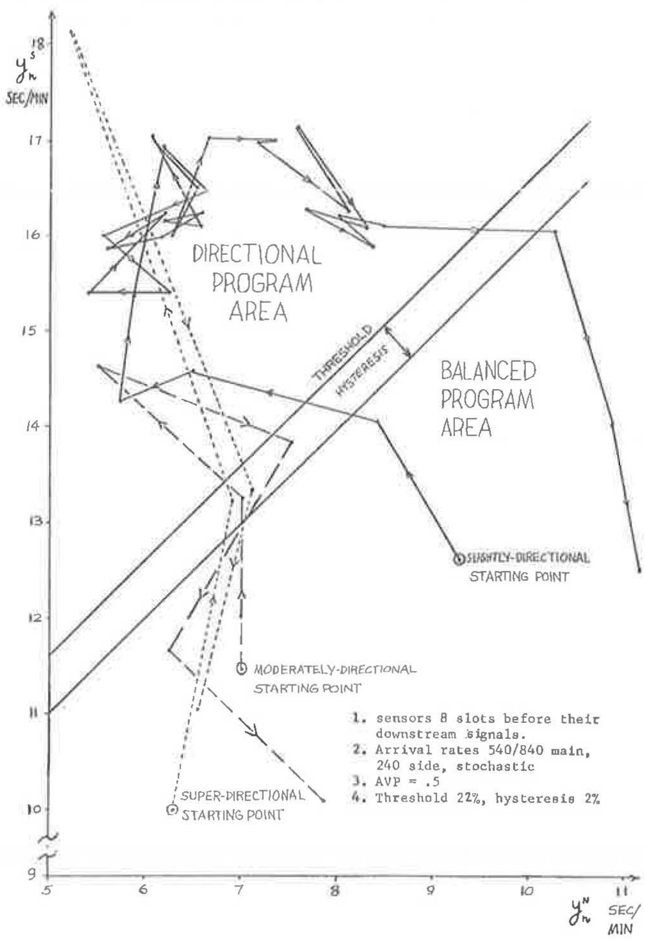
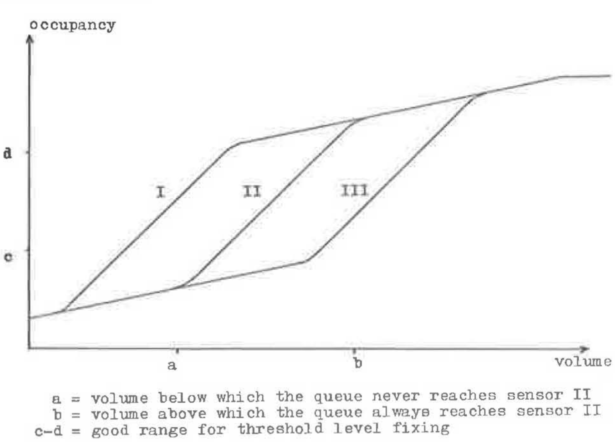


Figure 11. Sensitivity of occupancy to volume variations for three sensor locations.



Sensor Location

Ideally, the sensors in occupancy-based traffic control systems should be placed to enable the control algorithm to detect and reduce exessive queues accumulating at the intersections immediately downstream of each sensor, thereby attempting a reduction in delay and number of stops.

Placing each sensor far from its downstream signal tends to yield useful results in the sense of vehicular volume detection. However, such placement does not yield data on accumulated queues within a useful range. The time needed for such queues to reach the length necessary to significantly affect the smoothed occupancy parameter slows down the response of the system. Conversely, placing each sensor too close to its downstream intersection is meaningless because a minimal queue is to be expected most of the time, and sensitivity to queue variations would be low. Two sensors placed on one link can help in accurately determining the length of a queue. However, in the context of the traffic control algorithm discussed here, the selection of one sensor location (on the sensed link) at an appropriate distance from its downstream intersection should suffice for the provision of proper control data. After numerous trial simulations, the sensor locations were selected to be eight vehicle slots behind their respective signals on the central link of the four-intersection corridor [1 vehicle slot = 6.7 m (22 ft)]. Signal-system manufacturers generally recommend locating the sensors as far away from probable queues as possible yet at locations most likely to reflect a change in flow necessitating a change in program. This ambivalence is a result of a combination of the need for fast response and apprehension about queues reaching the sensors. However, it is precisely the placement of a sensor in an area that may be affected by queuing vehicles at certain arrival rates that allows differences in flow conditions between the two corridor directions to be easily detected. The location of a sensor in a spot sensitive to certain queues ensures program switching when the current control program does not handle a queuing problem adequately. Thus a better chance for matching the control program to the flow conditions exists. A directional program need not be invoked when flow conditions are not equal in the two corridor directions as long as the control program in effect is adequate for handling these conditions so that no excessive queues occur. Sensor location should be selected so that the queue affects the occupancy parameter to provide a program transition when volume in the dominant direction is so large that the balanced program cannot handle it well. Figure 11 shows qualitative sensitivity curves of the occupancy parameter in relation to directional volume for three sensor locations. The first sensor is closest to its downstream intersection, and the third is the farthest away.

Symmetric placement of sensors in both corridor directions in relation to their downstream intersections is advocated. Potentially bad results of gross asymmetric sensor placement occur at balanced flows because a sensor in one direction is occupied by a signal-caused queue more often than the sensor located in the opposite corridor direction is, thus forcing the system into a directional program that attempts to alleviate the occupancy discrepancy and sends the system back to a

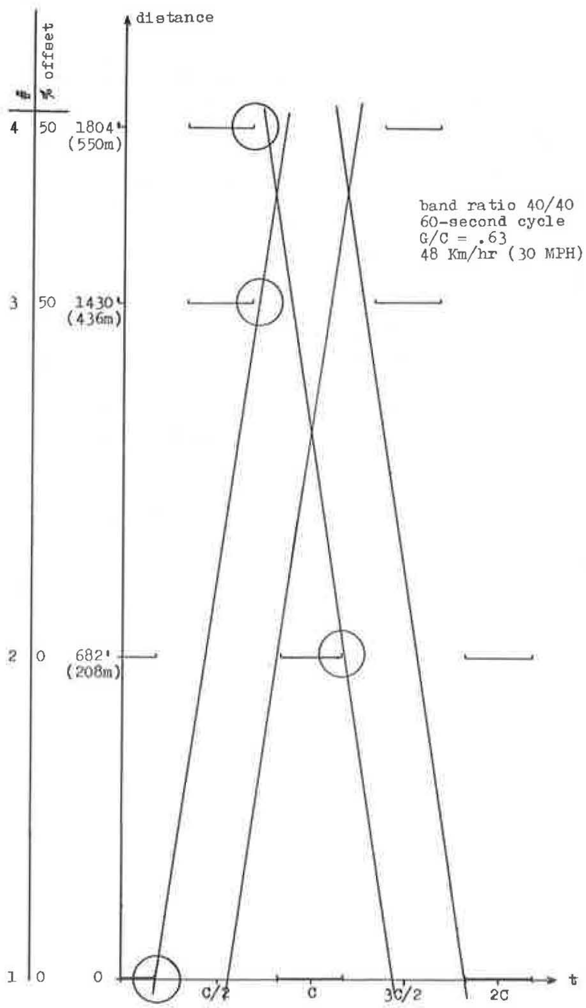


Figure 12. Average traffic program causes queue bias.

balanced program, which starts the process anew.

Queue Bias

Care should be exercised in calculating the control programs used. The use of band-maximizing techniques would generally result in the creation of a queue bias on the sensed link even though the sensors are placed symmetrically with respect to their downstream intersections. The bias problem may be serious enough to affect the behavior of the control systems, because the threshold level is modified by queue bias. Figure 12 shows the occurrence of queue bias due to the locations of the beginning and the end of each green phase in relation to the through band. The resulting simulated queue bias is shown in Figure 13 in terms of an occupancy-difference bias.

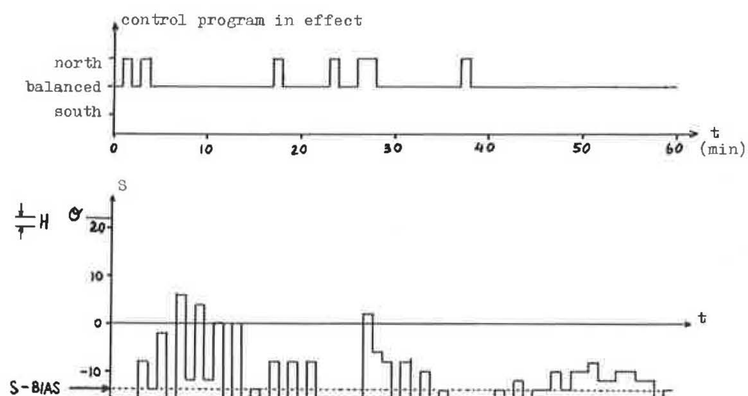
The circles drawn in Figure 12 point out the critical points causing unequal queues on the sensed link between intersections 2 and 3. The average queue at intersection 2 (going from 3 to 2) is larger than the average queue at intersection 3 going in the opposite direction. Hence, a larger occupancy value is derived, on the average, in direction 2 (intersection 3 to intersection 2). The green band is limited at the beginning of the platoon in direction 2 at intersection 2, although in direction 1 the leading edge of the platoon is limited at intersection 1 and intersection 3 allows for some lead time to clear at least a portion of the queue consisting of side-turning traffic and main-traffic residue, before the main platoon arrives from intersection 1. The arrival rates of 840/840 are sufficiently large to cause significantly larger queues or shock waves or both over sensor 2 than would be caused over sensor 1.

Queue bias was corrected in some of the simulations by incorporating a corresponding shift in the decision thresholds. An alternative approach would be to change the method of calculation of the control programs in order to get equal queues when arrival rates are equal. This could be achieved by shifting the offsets derived from band-maximizing methods to equate queues in both directions on the sensed link.

Control-Program Transition

Two program transitions were tested for their effect on

Figure 13. Negative bias in the S parameter and its effect on system behavior by modifying the threshold level for deterministic arrivals.



1. Sensors 8 slots before their downstream signals
2. Mildly-directional control-program set
3. Averaging period: AVP = .5
4. Arrival rates: 840/840 main, 300 side
5. Initial arrival rates: 540/840 main, 300 side
6. Threshold = 22%, hysteresis = 2%
7. Aggregate delay = 24,420 veh sec/hour

systems stability. The dwell type of transition (displaying main street green at each intersection until transition there is complete) was compared to the immediate type of transition (transferring immediate control to the new program subject to minimal phase durations). No significant difference in system behavior was detected, but the aggregate delay in the case of immediate transition is generally slightly lower, even though the program oscillation frequency is generally higher, and more transitions occur when this type of transition is used because no new transitions are initiated while a transition is in progress.

SUMMARY

Instability, as evidenced by unnecessary switching among offset programs in a library, does indeed occur for various combinations of control parameters. These instabilities occur mainly because of the development of unequal queues and shock waves on the sensed links. When these differences result in an occupancy difference that surpasses the threshold level, oscillation in control-program implementation occurs if the directional program invoked is sufficient to return the decision variable to a level lower than the hysteresis-modified threshold. These results bear out the general advice given by system manufacturers who recommend placing the sensors as far away from downstream intersections or from expected queues as possible. The manufacturers' recommendations for the use of occupancy as the decision variable historically evolved from the occurrence of saturated conditions or road blockages, which yielded false volume reading. By switching to occupancy as the decision variable, the equipment manufacturers were trying to improve the reliability of sensor information in relation to actual field conditions. However, the case in which occupancy should yield better results than volume is precisely the one in which instability will potentially occur. Cases in point are those of saturation or road blockages that occur in the vicinity of sensor locations. Similar results are anticipated from analogous studies of volume plus occupancy control now in progress.

The use of a threshold level with a large hysteresis band is strongly recommended whenever occupancy sensors are used to their full potential in detecting queues. Such a setting ensures that a directional program will remain in effect through most of its useful range rather than having the balanced control program take over at an inappropriate time, starting an instability cycle. The technique used in this study may be used to simulate other control algorithms, the feasibility of which in actual use is being investigated.

That the vast majority of previous simulations were used to test control programs on specific, static traffic-flow conditions rather than complete control algorithms is surprising. This situation will undoubtedly change. However, efficient simulation programs are necessary to meet this end because such an undertaking requires the observation of control-algorithm operation over long periods of time with a range of parameter settings.

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