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SIMULATION ANALYSIS OF TWO ADJACENT TRAFFIC SIGNALS

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The traffic delay and signal timing offset of adjacent signalized intersections are studied by stochastic computer simulation. The emphasis is on the effect of turning movements on traffic signal coordination. Coordination sychronizes the flow of traffic through a sequence of signals in order to minimize delays and stops. It's application is traditionally restricted to major thoroughfares where turning movements from side streets are insignificant. This study attempts to show that there are benefits of coordination for some combinations of side street turning traffic and how to obtain the optimal offsets from the simulation model.

INTRODUCTION

The high volume of urban roadway traffic has prompted the installation of an increasing number of traffic signals. Although signalization resolves traffic conflicts at the intersections, it causes delays and stops. The principle of optimal traffic control is to improve system mobility with a minimum of delays and stops. Delays and stops are not only annoying and costly to the drivers but they also add to air pollution and energy consumption. Traffic engineers often attempt to coordinate the traffic signal operation of adjacent intersections that are near to each other. Coordination is useful to move groups of vehicles through a group of signals without stopping and/or with a minimum of delays. The typical application is a progressive system that offsets the green periods at adjacent intersections relative to each other according to a desired speed of vehicle progression.

Signal coordination by progression is applied usually only to major highways or thoroughfares where the volumes of side street traffic turning onto the main roadway are insignificant. Undoubtedly, there are also circumstances that may benefit from coordination even though there are high volumes of side street turning traffic. However, it is difficult to obtain the generalization of a most efficient traffic control scheme for all circumstances. This is because of the considerable variations in the traffic volumes, roadway features, and driver behavior. The analysis becomes even more complicated when a group of adjacent signals are taken into consideration together.

Computer simulation is most suitable for dealing with problems such as the analysis of traffic signal operations. The process of vehicles arriving and leaving a traffic system is a well defined and simple queueing process. Moreover, in using computer simulation for the analysis of signal operations, the main purpose is to compare alternative strategies. The relative merits of alternatives are generally invariant to numerical sensitivity. Although it may be difficult to accurately ascertain the details of all the underlying stochastic processes and traffic phenomena, the optimal signal settings often do not depend on the details of the simulation model.

The purpose of the present study is to show that coordination of adjacent traffic signals justifies serious consideration independent of the volumes of turning movements. Furthermore, this study attempts to demonstrate that computer simulation is not only an effective tool for traffic signal programming but is also possibly the only tool available for dealing with the optimal control of a group of adjacent traffic signals. Although this study does not cover all the issues of adjacent signalized intersections and despite the assumptions and simplifications, the results suggest some measures for traffic signal controls and the practicality of using a stochastic computer simulation model for signal operation analysis.

SIGNAL OPERATIONS

Most traffic signals have three indications, green, amber and red. These are also called aspects. The arrangement of the sequence of displays is called a phase. During a phase, one or more traffic streams receive the same green or red indications. The traffic conflicts are resolved by the application of separate phases in a signal cycle. The simplest is a two phase signal, which alternately gives the green to each of two intersecting roadways.

One important parameter in signal programming is the cycle time. Too long a cycle time may cause longer queues and waiting times. Too short a cycle time may lead to a high percentage of time wasted during the switch between phases. In general, longer cycles are more efficient for the throughputs, which are important in reducing congestion and overall system delays when traffic volumes are near or beyond saturation. Shorter cycles are usually associated with lower traffic volumes when capacity is not a major concern.

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Another set of important parameters are the cycle splits, the distribution of the time within a cycle to the different phases. The allocation of green, amber and red indication time to each approach and traffic movement is complex. On the one hand is the concern for system efficiency. On the other hand is the concern for fairness in treating the various flow directions. In setting the cycle split, effective green time and lost time are key elements. Effective green time is defined as the time from the beginning of green period of the phase gaining the right-of-way to the end of the amber period of the phase yielding the right-of-way. Or, it may be defined as the cycle time minus the red time and the lost time.

Lost time consists of two parts: the starting delay at the beginning of green and the subsidence of flow during the amber phase. It corresponds to the period when there is no vehicle in the intersection. Starting delay is the time required for the lead driver/vehicle to respond to the green indication and to move from the stop line to the intersection. In practice, lost time due to starting delay is variable not only because of the widespread variation of drivers' reaction but also because of the possible existence of vehicles from the previous phase not yet clearing the intersection. The subsidence of flow during the amber period is also called the clearance time for the last vehicle entering the intersection. However, it is well known for vehicles that are close to the intersection to continue to proceed into the intersection well into the amber period. Some would even run the red light beyond the amber. Sometimes, an all red period is used to protect driver safety. In that case, the lost time is the intergreen time between successive phases. The relation between cycle time, effective green time and lost time are shown in Figure 1.

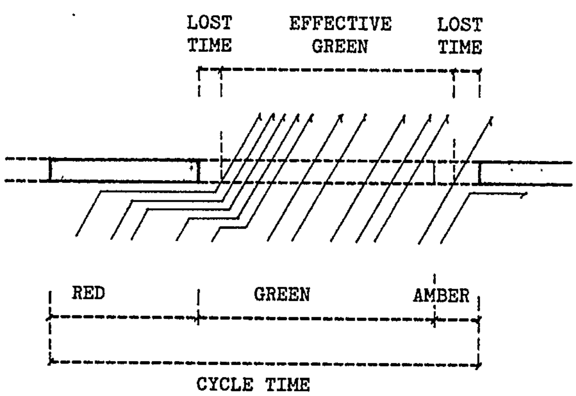

Figure 1. The Elements of a Signal Cycle

In general, signal offset is defined as the beginning of the green phase measured from a master reference. Therefore, the offset of one signal to another is referred to as the "difference-of-offset". Here, the offset between two adjacent signals is simply called "offset" for convenience. Common offset schemes are simultaneous, alternative, and progressive. However, progressive system is difficult, if not impossible, for an urban network. A good progression for a given direction or street is not necessarily beneficial for an opposite direction or for another street in the system. Sometimes, it is difficult to distinguish "major" and "minor" streets. Unequal spacing between signalized intersections also creates problem for a progressive system. A compromise is to deal only with delays. The delays between two adjacent signalized intersections are functions of the offset relative to each other. The delay/offset relationships can be combined for a series of adjacent signals. This allows the analysis of optimal offsets for a network.

TRAFFIC MOVEMENTS

Traffic flow may be treated as deterministic or random. Which treatment to use is important in the discussion of arrivals and queue discharge. It is frequently observed that at an intersection, some vehicles arrived to form a queue during the red period. The dissipation of the queue during the green period is a more or less deterministic process. After the queue has been discharged, vehicles arrive and pass through the intersection without joining a queue. These vehicles form a process identical to the arrival process for all vehicles arriving from the same stream.

Vehicle arrivals at an isolated intersection have been found to fit a Poisson process. The negative exponential distribution of headways in a Poisson process allows some very short headways. In traffic analysis, a shifted exponential distribution is used instead, so that very short headways can be eliminated. For vehicles traveling from one signalized intersection to another, the arrival process is a complex combination of random and deterministic elements generated by the influence of all the upstream signals each vehicle passes through.

Traffic platoons are created when a queue is discharged. As the platoon progresses downstream, it is dispersed gradually as vehicles in the platoon vary their speeds and as vehicles leave and join the stream. Platoon dispersion generally can be ignored for closely spaced intersections.

DELAYS

The delays to the traffic is always an important criterion in signal optimization, although other criteria must also be considered. Total delay can be obtained from the cumulative functions of arrivals and departures, as shown in Figure 2, where it is expressed as the total waiting time accumula-

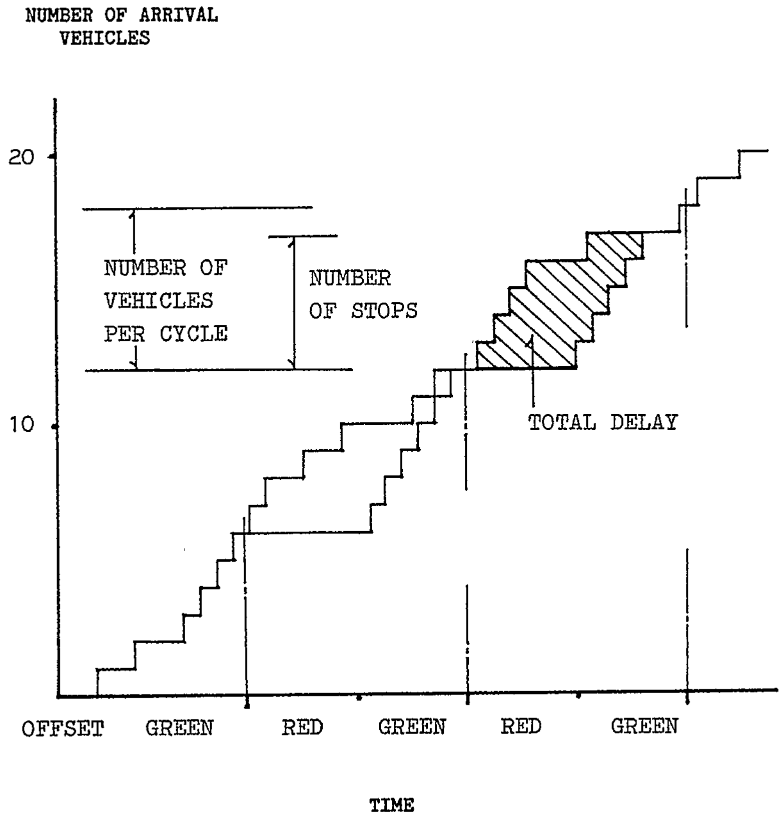

Figure 2. Computation of Delays and Number of Stops

tion from the beginning of the red period to the full discharge of all queueing vehicles.

SIMULATION MODEL

In the simulation model, only two adjacent signalized intersections are involved. As mentioned previously, the delay/offset relationships between pairs of adjacent signals can be combined to determine the total delays from a series of signals. The upstream intersection is assumed to be independent of other intersections. Accordingly, the vehicles approaching from three directions are assumed to be random following shifted negative exponential headway distributions. Figure 3 is a depiction of the geometric characteristics of the two adjacent intersections simulated. In addition, it is assumed that there is no interaction between the straight-through, left turn and right turn traffic with any other traffic stream. All other traffic streams are ignored.

Two sets of variables and parameters are used in the simulation model. One set represents traffic flow characteristics. The other represents the signal settings. These variables and parameters are all the inputs used in the model. A common amber time for all approaches is used as an input variable, as well as offsets in eighths of the cycle time.

Traffic Flow Variables:

ST = upstrteam straight-through volume, vph
RT = upstream right turn volume, vph
LT = upstream left turn volume, vph
VT = total downstream arrival volume, vph
= ST + RT + LT

DQ1 = queue discharge rate for ST, sec/veh
DQ2 = queue discharge rate for RT, sec/veh
DQ3 = queue discharge rate for LT, sec/veh
DQ = queue discharge rate for VT, sec/veh

Signal Control Variables:

C = common cycle time, sec
G1 = green time for ST, sec
G2 = green time for RT, sec
G3 = green time for LT, sec
GG2 = green time for VT, sec

CL1 = lost time due to starting delay, sec
CL2 = lost time due to amber clearance time, sec

The ouput variables are average delay, average delay in queue, proportion of vehicles stopped, number of saturation occurences, and average number of arrivals per cycle. The analysis focuses mainly on the downstream intersection.

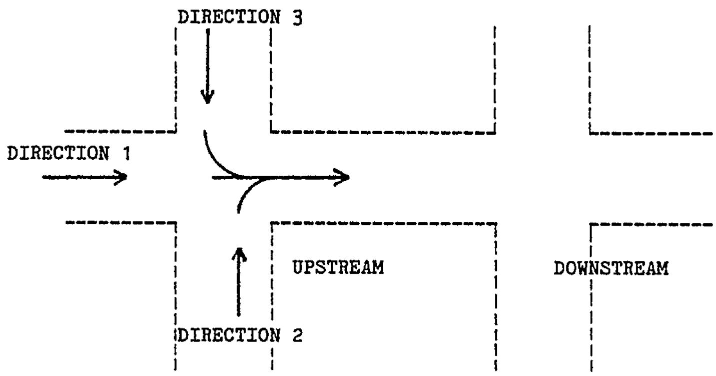

Figure 3. Geometric Representation of the Intersections

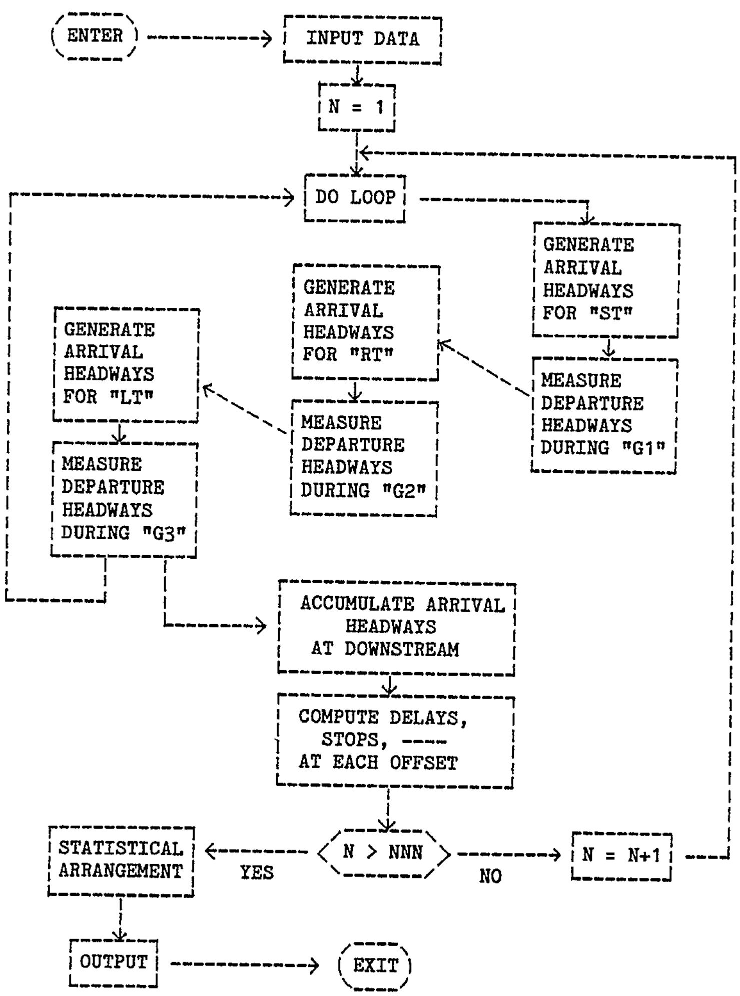

Figure 4. Flow Diagram of the Simulation Model

VALIDATION

The ability of the model to simulate delays accurately is checked against a delay formula developed by Webster. The Webster equation is intended for estimating signal delays for an independent approach that has random flow arrivals. Although a direct comparison between the simulation results and the Webster equation is not possible, the simulated results indicate that the model outputs are in line with Webster's equation.

The average number of vehicles generated for a cycle is very close to the input value. A check of the simulated delays against each other with different initial random number seeds also shows that initial seed values do not lead to any bias.

SENSITIVITY ANALYSIS

Sensitivity analysis of the delays with respect to the queue discharge rates has been carried out. It is found that both deterministic and variable (randomly distributed according to a normal distribution) discharge patterns produce almost identical delays. However, different discharge rates at the downstream intersection result in delays of different magnitudes, but all the rates give the same optimal offset. When different queue discharge rates are used for turning movements upstream, there is little difference in the delays at the downstream intersection. The conclusion is that for a given total flow, the delays at the downstream intersection are relatively insensitive to the upstream discharge patterns.

Three sets of lost time were also tested. They show only very minor differences in the delay/offset relationship. This result can be explained by that the formation of a queue, which principally determines delay, is not affected by the lost time. Therefore, the experiments conducted with the simulation model did not include investigations on the effects of discharge patterns and different lost times.

RESULTS

The simulation experiments are designed to change input variables one by one, while holding everything else being equal. If there are important interactions between variables, several levels of the variables are simulated. The variables that do not affect the delay/offset relationship are held at some representative levels. Output delays are computed for each of eight different offsets, in eighths of the cycle time. The travel time between intersections is not considered, because it would only shift the offset to a value which is determined by the fractional cycle in the sum of the offset time and travel time. The delay/offset relationship is investigated for the influences of cycle time, cycle split, traffic volume, traffic proportions, signal phase sequence. Also studied are average delay in queue, vehicle stops and saturation.

Since there is a variation of input parameters, a few more assumptions and conditions are prescribed to facilitate the specification of inputs. First is the assumption that the right turning flow is always equal to or greater than the left turning flow and less than the straight-through volume, i.e. ST>RT>LT. This condition only limits the analyses slightly, because ST, RT, and LT can be exchanged by altering the signal phase sequence and the offset. Second, the intersections and the approaches are conditioned to be undersaturated, namely, the total approach volume for the downstream signal is kept at a level less than 80% of saturation. A study of delays is not meaningful, because delays approach infinity as flow approaches saturation. The third condition is to keep the green time at the downstream intersection (GG2) at half the cycle time. For a queue discharge interval of 2 seconds, the saturation capacity for the approach of interest is 900 vehicles per hour. The total volume for the approach to the downstream intersection is, therefore, limited to 720 vph.

Finally, for the cycle split of the upstream intersection, two ways are used to determine the green times. One is to fix arbitrarily the ratio of the three green times, i.e. G1:G2:G3, regardless of the traffic volumes. Since there is no other traffic involved in the model, which may be unrealistic, this approach may not affect the study results. Several ratios of G1:G2:G3 were used. Another way is to use the Webster's equation of determining split, which attempts to balance the degree of saturation of all the approaches. This method provides a consistent relationship to the proportion of flows.

CYCLE TIME

Average delays decrease uniformly with decreasing cycle length, when traffic volumes and cycle splits are fixed. This result agrees with our knowledge that for undersaturated intersections, longer cycle times lead to longer average delays. However, the delay/offset relationship remains similar for different cycle lengths, as offsets are expressed in terms of the cycle length, rather than real time. As the cycle length approaches the minimum, the difference in delays between the best and worst offsets is in the order of one standard deviation. In the case of short cycle time, fluctuations in flow volumes may influence delays more than offsets. Since the minimum cycle length is not realistic because it precludes the existence of other flows, later experiments used a long, 80 sec, cycle length to enhance the effects of offsets.

TRAFFIC INDEPENDENT CYCLE SPLIT

These experiments were carried out with arbitrary green splits that are not necessarily related to the proportion of flows, while holding all other input parameters fixed. The proportions of 2:1:1, 3:2:1, 4:3:1 and 6:5:1 are used for G1:G2:G3. The straight-through green time G1 is always half the cycle length and equal to the downstream green time, GG2.

The delay/offset characteristics are influenced to some extent by the green splits as shown in Figure 5. However, the relationship is not particularly sensitive to small variations in the green splits. This is perhaps because G1 is fixed and delays are affected mainly by the volume of straight-through traffic, which is the dominant flow. One may infer that green time for the dominant flow is the most important in determining the delay/offset relationship. Thus, it is less important to consider the minor flows for fixed green splits. The effects of green splits that are proportional to the flows are discussed later.

TRAFFIC VOLUMES

Two types of changes in traffic volumes are considered in the experiments without changing the signal parameters. One is the changes in the total traffic volume. In general, delays decrease as total traffic volume decreases, but not proportionally. This again is well known: delays increase rapidly only when the flow approaches saturation. This general trend is independent of the proportion of the three flows.

When the proportion of the three flows, ST, RT and LT, is altered, delays fluctuate more with the signal offset. This is shown in Figure 6. For the same proportion of flows, the delay/offset pattern is the same for different total flows. The conclusion is that the choice of the optimal offset depends on the proportion of the flows but not so much on the total flow. Analysis shows that for the same signal settings, the best offsets are about the same for very different total flow volume and flow proportion. This indicates that the choice of offset does not have to be too precise.

SIGNAL PHASE SEQUENCE

Figure 7 shows typically the influence of the relationship between signal phase sequence and offset on the average delay. Figure 7 shows the delay/offset characteristics for two sequences: G1-G2-G3-G1 and G1-G3-G2-G1. Since the flow is highest for straight-through (G1) and slightly less for right turn (G2). The first sequence goes from the highest flow to the smallest flow, while the second sequence is just the reverse. There is a slight shift in the best offset between the two different flows but not for the two sequences. However, there is definitely a difference in the worse offset. In this sense, changing signal phase sequence may be useful for reducing the average delay, if the offset must be fixed. This feature should be considered by the traffic engineer when there are significant turning movements.

CYCLE SPLIT AND TRAFFIC PROPORTION

Cycle split and traffic volume have been discussed previously. However, in those experiments, these variables are unrelated to each other. Here, experiments are for changes in the traffic proportion and the associated changes in green splits. The green splits are set to yield equal levels of saturation for all three flow movements, as previously discussed. In general, the delay characteristics are similar to what have been seen thus far. However, the fluctuations in average delays with changes in the offsets are very pronounced. It is difficult to pin point a general relationship between average delay and signal offset. Figure 8 shows such an example. Although the effects are prominent, there is no obvious correlation. The results indicate that when green splits are set according to the proportion of flows, care must be taken to consider the effects of the signal program on adjacent signals.

RELATIONSHIPS BETWEEN PERFORMANCE MEASURES

This section discusses the relationship between the various types of performance measures: average delay, average delay in queue, percentage of vehicles stopped, and the number of saturation occurrences. Figure 8 shows the delay/offset relationship for average delay and average delay in queue. Despite a high correlation between the two, there are significant differences, particularly for the high values of offsets in Figure 9. Therefore, optimum offsets for the average delay of all vehicles and for the average delay of vehicles in queue may be different.

The percentage of vehicles stopped is closely related to the volume of total flow for a given set of signal timing. This is shown in Figure10. In general, the percent of vehicles stopped is correlated with the average delay. When the average delay is high, more vehicles would have to be in queue. When the average delay is low, few vehicles are required to stop. Therefore, signal coordination that minimizes stops would most likely also minimizes average delay.

In terms of the number of saturation cycles, there are few such occurrences when volumes are much below capacity. However, as flow approaches the saturation level, saturated cycles become more frequent. However, the number of signal cycles that are saturated relative to the signal offset is strongly correlated with the average delay. The offset that yields minimum average delay is also the one that demonstrates the fewest saturated cycles. A comparison of average delay and offset with saturation cycles and offset is shown in Figure 11.

In summary, a good offset for one type of performance measure is also good for another measure of signal performance. The accuracy required for the simulation model is not very important. When one measure cannot be easily modeled accurately, a substitute may be used. Since our objective for the simulation is not to measure performance quantitatively but is to determine some good and practical offsets for coordinating adjacent signals, some of our assmptions and simplifications are well justified.

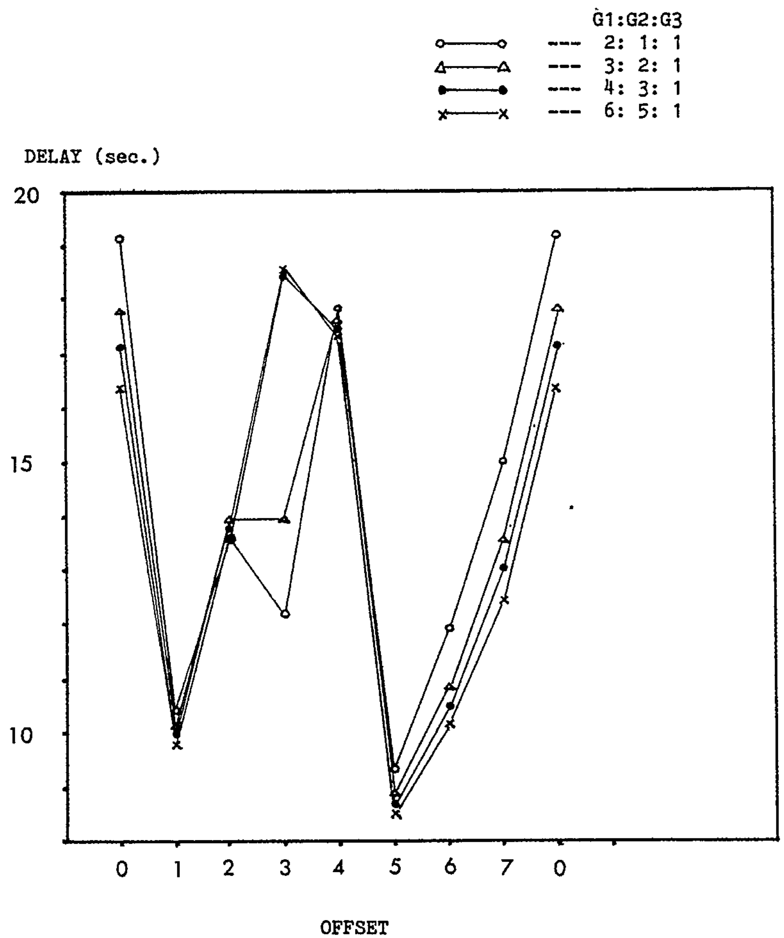

Figure 5. Average Delay versus Signal Offset for Different Cycle Splits (C=80 sec, VT=300 vph, and ST:RT:LT=3:2:1)

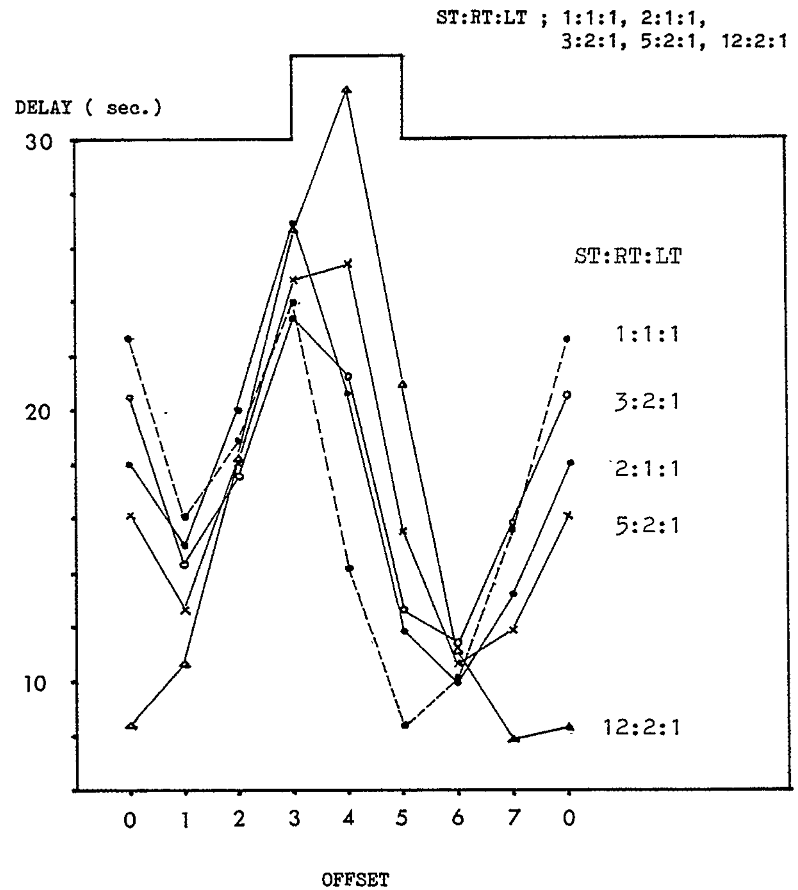

Figure 6. Average Delay versus Signal Offset for Different Proportions of Flow Volumes (C=80 sec, VT=600 vph, G1,G2,G3=40,30,10 sec)

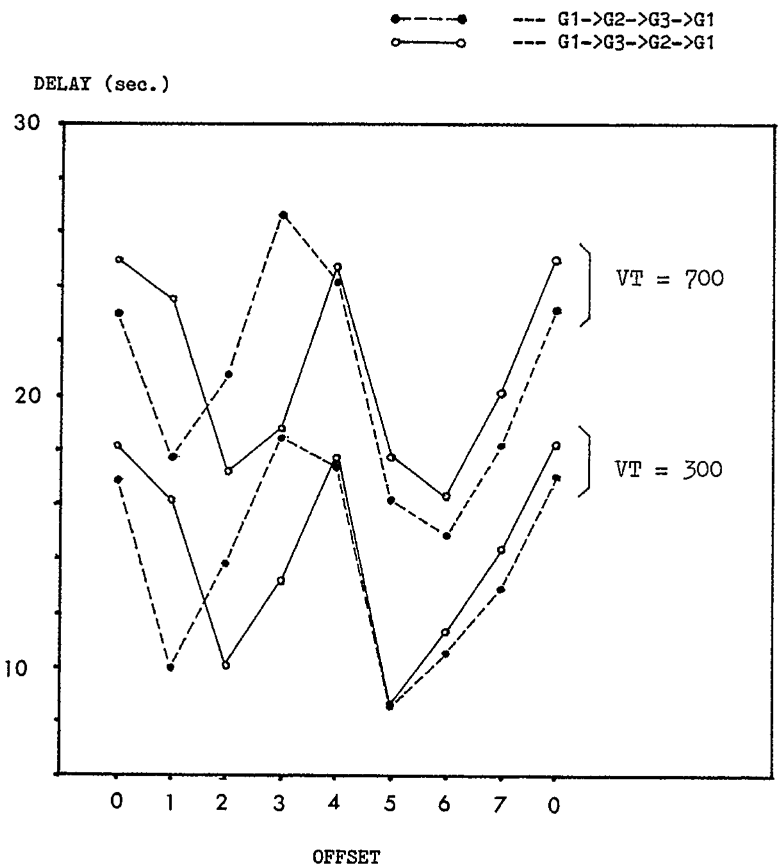

Figure 7. Average Delay versus Signal Offset for Different Signal Phase Sequences (C=80 sec, G1,G2,G3=40,30,10 sec, and ST:RT:LT=3:2:1)

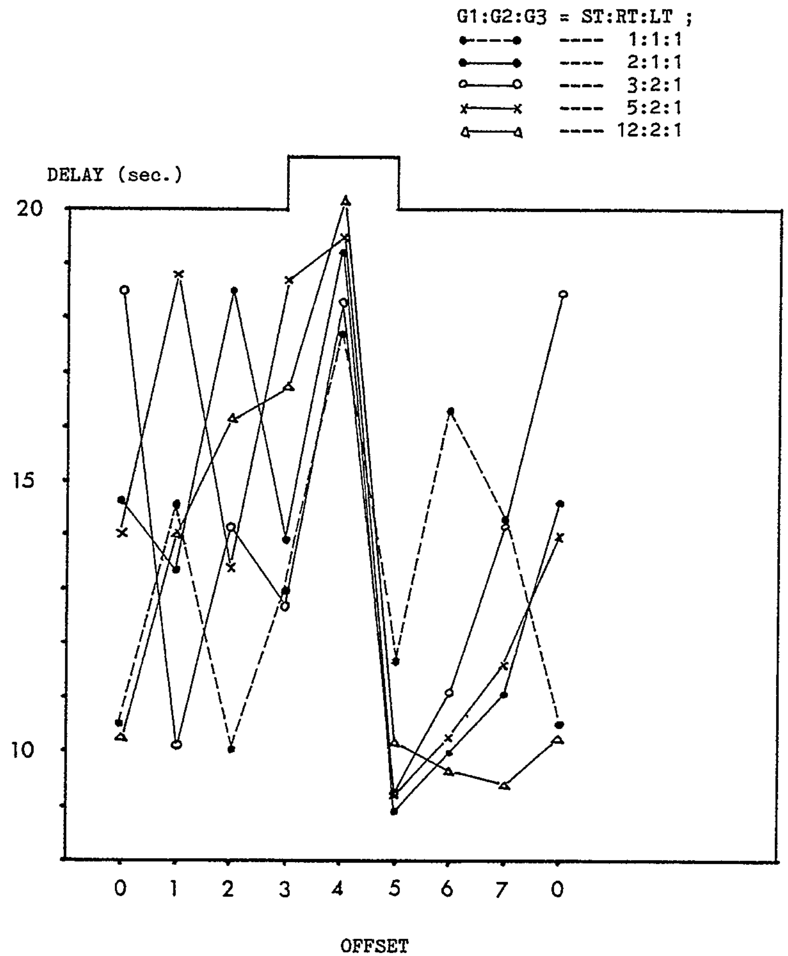

Figure 8. Average Delay versus Signal Offset for Different Volume Proportions and Cycle Splits (C=80 sec, VT=600 vph)

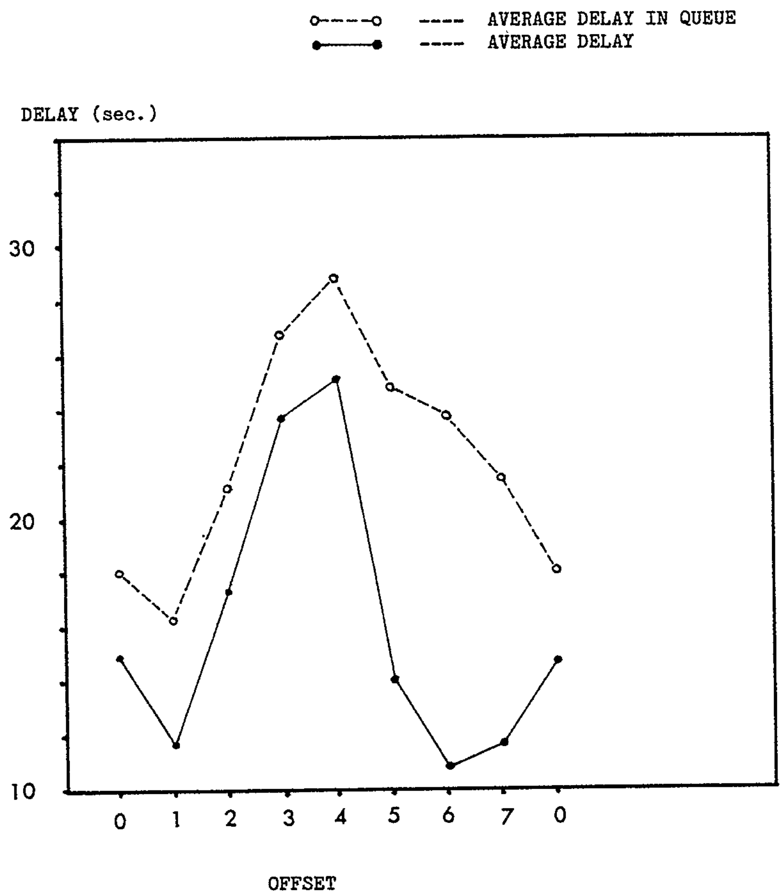

Figure 9. Average Delay of All Vehciles and Average Dealy for Vehicles in Queue versus Signal Offset(C=80 sec, G1,G2,G3=40,30,10 sec, VT=500 vph, and ST:RT:LT=5:2:1)

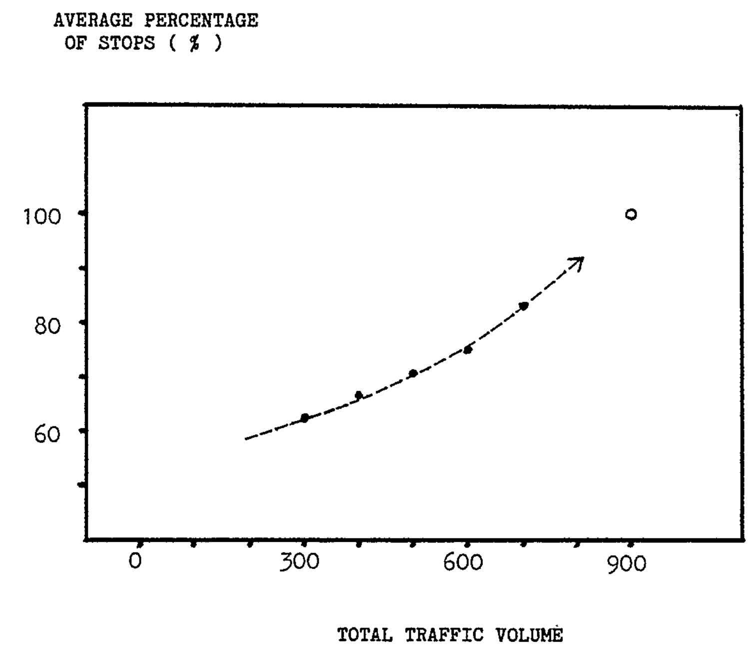

Figure 10. Average Percentage Stopped vs. Total Traffic Volume (C=80 sec, G1,G2,G3=40,30,10 sec, and ST:RT:LT=5:2:1)

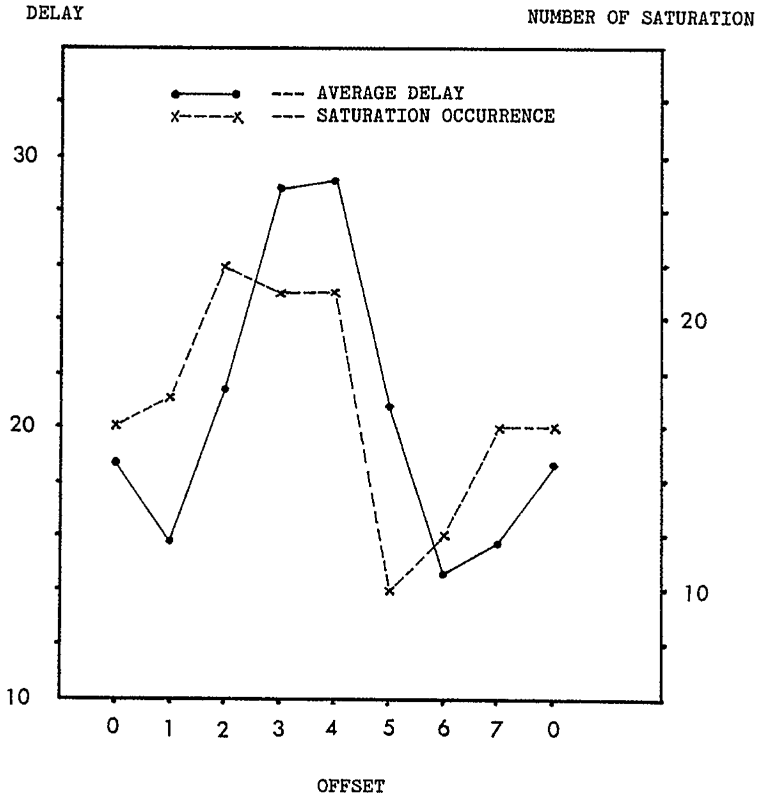

Figure 11. Average Delay and Number of Saturated Cycles versusSignal Offset (C=80 sec, VT = 700 vph, G1,G2,G3=40,30,10 sec, ST:RT:LT=5:2:1)

SUMMARY AND CONCLUSION

The purpose of this study is to analyze the relationship between traffic delays, traffic flow, and traffic signal operation for adjacent intersections. In particular, the study attempts to demonstrate the usefulness in coordinating traffic signals in urban areas. A computer simulation model is developed for the analysis of adjacent signal operations. The model shows that simulation is a useful tool for signal design analysis The details of the model, with its assumptions and simplifications, are not important for selecting good signal offsets. While the simulation model is directed at a pair of idelaized intersections, it may be possible to extend the model for specific applications.

The analyses about delays and offset were carried out with many feasible sets of input parameters representing signal settings and traffic flow. Some highlights of the results are as follows. First, queue discharge rate and lost time do not affect the delay/offset relationship, although the queue discharge rate does affect the amount of average delay. Similarly, the delay/offset characteristics are not influenced by the total traffic volume or the cycle length.

The delay/offset relationships are most sensitive to cycle split, green phase sequence, and the proportion of flows. The use of green splits corresponding to equal saturation levels for the different flows creates problems for identifying the suitable coordination with the downstream signal. In general, the selection of signal offset is complicated and a simulation model seems to be particularly suited for this purpose.