Simulation and Control of Traffic on a Diamond Interchange

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Signaling strategies that control left-turning traffic on a diamond interchange are evaluated by simulation. Although the simulation and control strategies were designed for a particular interchange, each may be adapted to the intersection of other one-way pairs of arterials. The simulation method is briefly discussed, and four related control strategies are presented. Evaluation of these strategies based on average and maximum transit times through the interchange indicates that choosing signal features can significantly profit from the use of short-term average volume information. A flexible strategy based only on queue lengths gives good but not entirely satisfactory performance.

One of the more challenging problems in designing controlled access highways is providing for the interchange of traffic on two or more intersecting facilities. The diamond interchange is now being used for this purpose because it requires less area than the traditional cloverleaf. A major disadvantage of the diamond interchange, however, is that vehicles desiring to make a left turn will, in general, be required to stop. It is therefore important that suitable signaling methods be developed to optimize interchange performance when traffic volumes vary (1).

The object of our research was to simulate the I-291 and Rt-15 diamond interchange in Newington, Connecticut, and to use this simulation to evaluate several methods of controlling left-turning traffic. This interchange, shown to scale in Figure 1, has three levels, one for each throughway and a third for traffic interchange. Simulation has been limited to the interchange level and then only to that portion of traffic turning left. Although the discussion and results presented here apply primarily to this particular interchange, it will be clear that the simulation and signaling strategies can be adapted to the intersections of other pairs of one-way arterials.

Figure 2 shows, schematically, the simulated portion of the interchange and the lane designations used. Each lane is approximately 134 m (440 ft) in length including the input lanes denoted North 01, North 02, West 01, West 02, and so forth. The progress of each vehicle is simulated from "birth" time until it exits at the final intersection. Thus, a vehicle arriving from the south, for example, is assigned to the shorter of queues South 01 and South 02. If South 01 has the shorter queue, the vehicle proceeds successively through lanes South 01, South 2, East 1, and exits at the north intersection.

SIMULATION METHODS

Definition of Terms

For convenience in discussing the material, several definitions of our terms are given as follows.

Interior or circulating lanes—those lanes denoted 1, 2, and 3 in Figure 2 and used by vehicles to accomplish a left turn,

Input lanes—all lanes denoted 01 and 02 used by vehicles to enter the interior lanes,

Occupancy lanes—lanes denoted 11 and 12 (not shown in Figure 2) [these lanes are a portion of input lanes 01 and 02 extending about 92 m (300 ft) from the intersection; occupancy lane queues are used in certain signaling schemes to determine the starting time and duration of the next green interval],

Phases A and B—light sequences experienced by vehicles on the circulating lanes and on the input lanes, respectively,

Intersections north, south, east, or west—intersections in Figure 2 at which vehicles enter respectively on input lanes designated north, south, east, and west,

Transit time for a designated lane—total time spent in the lane, including travel time, waiting time at a red light, if any, and time required to cross the subsequent intersection,

Total transit time for vehicles entering north, south, east, or west—total time spent in the interchange, starting 134 m from the first intersection, terminating when vehicle discharges at the last intersection [thus the transit time for a vehicle entering north is time spent in North 01 (North 02) plus time spent in North 2 (North 3) plus time spent in West 1 (West 2)],

Differential—time interval by which phase B green at one intersection precedes phase B green at the diagonally opposite intersection,

Maximum contents of a designated lane—maximum number of vehicles encountered in the given lane during the course of the simulation, and

Maximum time to leave system—longest total transit time encountered by any vehicle entering from a particular direction.

Traffic Flow Simulation

Two simulations of traffic flow within the interchange have been developed using the general purpose system simulation (GPSS) package (2). Program A maintains the position and velocity of every vehicle within the interchange area of Figure 2. This information is updated every second on the basis of a simple car-following model in the form of a nonlinear equation (3, 4, 5). Vehicles in program B, on the other hand, move between intersections in a given or computed travel time. This avoids the necessity of storing and updating position and velocity and saves substantial computer time. It is more difficult in this case, however, to realistically simulate large variations in traffic volume. All lanes, except occupancy lanes, are 134 m long. In program B, the travel time over each 134-m lane is a random number for each vehicle, uniformly distributed over 12.5 to 15.5 s.

Vehicles moving through an intersection in program A do so according to the car-following model. If a vehicle is required to stop, it will start up again at a maximum specified acceleration. The delay in achieving a steady flow is automatically provided by the model. Start-up delays must be built into program B, however. This has been accomplished by assigning the time in seconds required for each vehicle to pass through an intersection according to the following table.

Figure 1. Scale plan of Rt-15 and I-291 interchange.

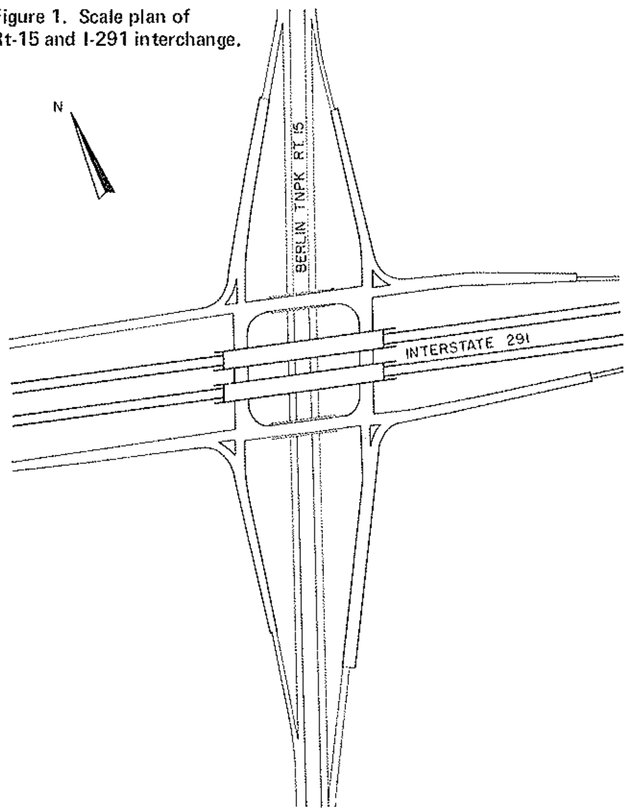
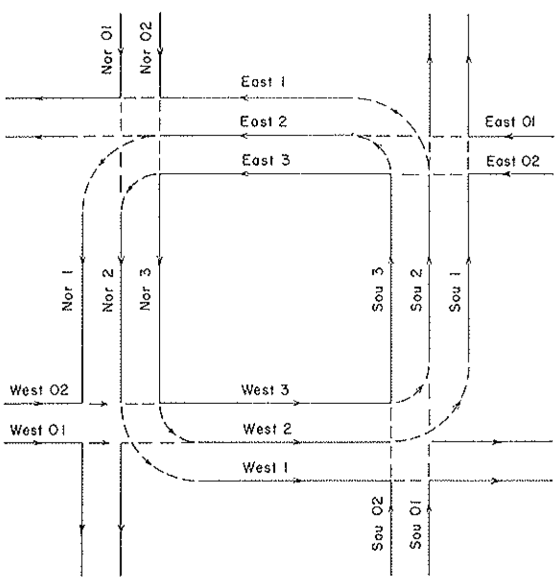


Figure 2. Interchange schematic with lane designations.



Time From Start of Green Phase (s)	Time Required to Cross Intersection (s)
0 to 3	4
3 to 6	3
>6	2

If, for example, three or more vehicles are stopped, the first vehicle will cross the intersection 4 s after the start of the green phase; the second vehicle will follow 3 s later; and subsequent vehicles waiting will follow at 2-s intervals. If, however, the first vehicle in the lane arrives at the intersection 3 to 6 s after the light turns green, it will require only 3 s to cross the intersection, and so on.

Each program maintains records and calculates, at the conclusion of the simulation, the average of the total transit times through the interchange, average transit time through each lane, distribution of transit times, maximum and average contents of each lane, and other aspects. This information is useful for evaluating the performance of different signaling strategies.

Vehicles are generated in both programs by using random numbers to establish the birth time of each subsequent vehicle. The interval between generations can be given any probability distribution desired. A truncated exponential distribution corresponding to a Poisson process with a 1-s mean has been used in all simulation studies thus far. An adjustable multiplier that provides the average time between arrivals necessary to produce any desired traffic volume is then used for each direction.

The car-following model in program A has been adjusted so that statistics for the program correspond well with those of actual traffic on a short span of two-lane highway that includes one intersection. Because program A is less efficient, however, it has been used primarily to check the validity of program B. In general, the two programs are in good agreement except when traffic volumes are unusually heavy, which makes program A give somewhat longer transit times. Because of this agreement, results will be provided for program B only.

Signal Control

In the GPSS simulation, signals at intersections designated north, south, east, and west are controlled by two transactions that circulate in a loop of instructions. Variations in the signaling strategy are introduced by changing these instructions.

In general, all signal control strategies are designed to allow each vehicle, once it has entered the circulating lanes of Figure 2, to proceed without stopping. Assuming a nominal 15-s travel time between each intersection, this means, for example, that the east phase A green must commence within 15 s after the start of south phase B green. Similarly, north phase A green must begin within 30 s of the start of south phase B green (and vice versa). These requirements place strict constraints on the signal sequence.

Figure 3 is a simplified flow diagram indicating the manner in which traffic signals are controlled in the simulation. At the start of the program, signals are all set at phase A green. Fifteen seconds later, lights at north and south are set at phase B green for 9 s. Following the start of phase A green, north and south, there is a 15-s pause, during which platoons entering from north and south move past the west and east intersections, respectively. Then a decision is made concerning the starting times and durations of the phase B green at east and west. Fifteen seconds after the end of phase B green east or west, whichever occurs first, the starting times and durations of the north and south phase B green are calculated. The process then continues in this manner.

Signaling strategies ranging from a fixed cycle to a flexible traffic responsive strategy can be incorporated by changing the procedure by which starting times and durations of the phase B green intervals are calculated. Although Figure 3 is a simulation flow diagram, it also shows how a special digital controller might function when supplied with information about queue lengths and short-term average traffic volumes measured at the input to each intersection.

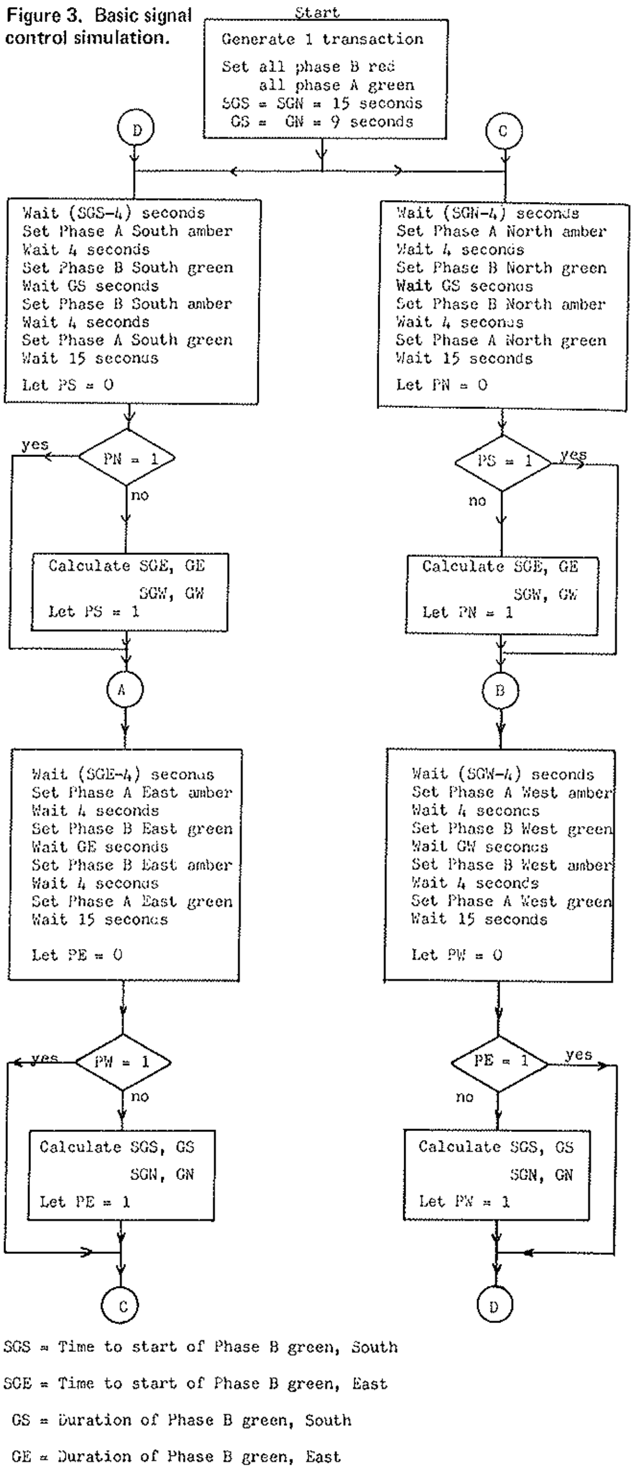


Figure 3. Basic signal control simulation.

Omitted from Figure 3, for simplicity, is the task of setting the intersection crossing times according to the previous table, as required in program B. (This is required in the simulation but not in actual implementation of the signaling strategy.)

SIGNALING STRATEGIES

Four signaling strategies have been evaluated, and each is designed to virtually eliminate stopping within the interior lanes. Method A is equivalent to a procedure suggested by the Traffic Engineering Division of the Connecticut Department of Transportation (DOT). The reader will find it helpful to refer to Figure 2 in following the description of these signaling methods.

Method C

This is a simple strategy in which signals at north and south are synchronous, and signals at east and west are synchronous. Phase B green starts simultaneously at north and south and terminates when occupancy lanes North 11 and South 11 are both empty, or after 26 s, whichever occurs first. Allowing for a 4-s amber period, this means that phase A green will commence a minimum of 30 s after the start of phase B green. Fifteen seconds after the start of north and south phase A green, phase B green starts at east and west. A typical phase B sequence is shown in Figure 4 where the 15-s nominal transit time over interior lanes is assumed.

Method B

Method B adds flexibility to method C above by permitting north and south (and east and west) to use different interval lengths for phase B green. Fifteen seconds after phase A is green at both east and west, the number of vehicles in occupancy lanes North 11 and South 11 are observed. If both occupancy lanes are full (13 vehicles or more) or neither is full, phase B north and south act synchronously as in method C. If one lane is full and the other is not, then a differential (Δ) is calculated according to the formula discussed below. Phase B green then starts Δ s early for the longer input queue. In Figure 5, for example, South 11 is full; North 11 is not; and Δ is calculated as 7 s. Phase B green south starts $\Delta = 7$ s before phase B green north and has a duration of $25 + \Delta$ s. Phase B green north lasts for $25 - \Delta$ s. This ensures that phase A green north will begin 29 s (that is, 25 s plus a 4-s amber) after the start of phase B green south, and vice versa.

Fifteen seconds after both north and south have switched to phase A green, a similar calculation is made for the east and west intersections to determine a differential Δ. If $\Delta \neq 0$, then east or west phase B green is delayed Δ s, and so on.

The differential Δ has been calculated in several ways. A formula suggested by the Connecticut DOT is

$$\Delta = \begin{cases} 16 - (15N/10), & \text{when } N < 10 \\ 1, & \text{when } N > 10 \end{cases} \qquad (1)$$

where N is the number of vehicles in the smaller queue. Another expression is obtained by noting that if $N = 2$ or more in the smaller queue and the time required to dissipate an N-vehicle queue is $2N + 3$ s, then it is desirable that

$$\text{green time, full queue/green time, shorter queue}$$
$$= (25 + \Delta)/(25 - \Delta) = [2(13) + 3]/(2N + 3) \text{ or}$$
$$\Delta = [(26 - 2N)/(32 + 2N)] \times 25, \text{ when } N > 2 \qquad (2)$$

Simulation has been carried out using Equations 1 and 2 and similar relations. There seems to be no great sensitivity in the choice of Δ, and results presented are for Equation 1.

Method A

An early start feature may be added to method B to provide improvement in some situations. Suppose, for example, that the queue in lane West 11 is depleted E s before East 11, and that as a consequence phase B green

Figure 4. Typical phase B signal sequence where differential (Δ) is not required.

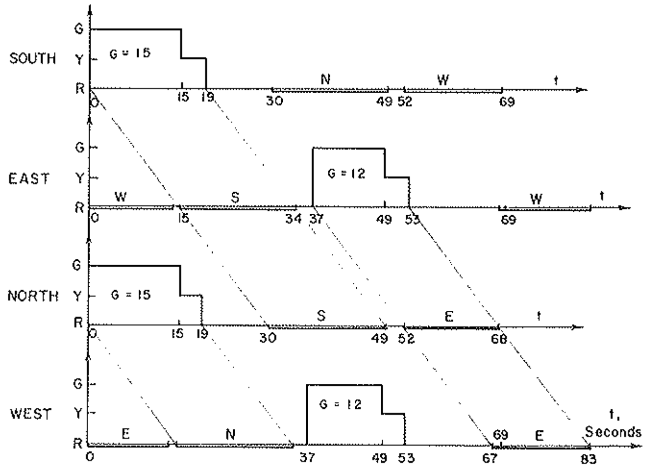
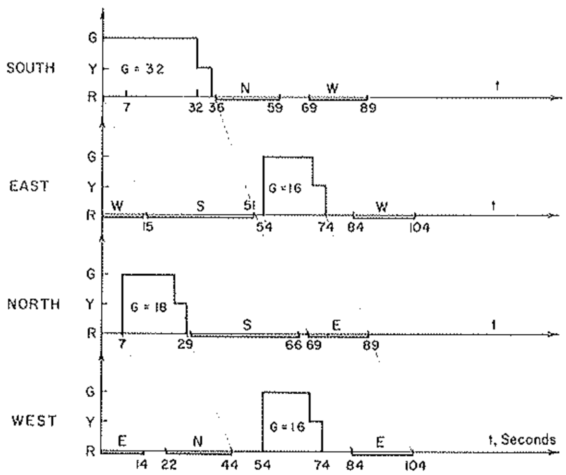


Figure 5. Typical phase B signal sequence where differential of 7 s is required for south.



west is terminated E seconds before east is. Fifteen seconds after the termination of phase B green west, the north-south differential is calculated. If Δ > E and favors south, then phase B green south is started immediately. If Δ < E and favors south, then phase B green south starts E - Δ s later. If Δ = 0 or favors north, then no early start can be used in this case. Thus, when differential Δ ≠ 0, the direction favored may be able to start earlier than in method B and thereby to make more efficient use of the interchange. If Δ = 0, no early start is employed.

Method D

Method D is a simple fixed sequence designed to accommodate the given volumes in a more or less optimum fashion. If one examines Figure 5, where Δ = 7 s is used, it will be noted that west phase B green can start at 44 s, rather than wait until 54 s to coincide with phase B green east. Vehicles entering the interior lanes from west at 44 s or after will encounter phase A green 30 s later at east and may therefore exit without stopping. This observation has been used in Figure 6, which illustrates a sequence similar to that of Figure 5 with phase B green west advanced for volumes as in Table 1. The phase B green durations approximate proportionately the volumes of 500, 900, 400, and 300 vehicles/h for north, south, east, and west, respectively.

Observe that the total phase B green is about the same in both figures, but Figure 6 achieves this in 80 s, while Figure 5 requires 89 s. Thus the scheme in Figure 6 is about 10 percent more efficient for uniform traffic flow. Traffic does not arrive uniformly, even in the simulation, so it is questionable whether the fixed sequence of Figure 6 will, in fact, outperform the more flexible strategy of method C even when traffic volumes average those for which the signal sequence of Figure 6 was designed.

SIMULATION RESULTS

Tables 1 through 3 summarize performance for three different volume conditions. All simulations are continued until 1000 vehicles exit from the system. This requires about 30 min (real time) for the volumes of Table 1 and 25 min for Tables 2 and 3. Input volumes in Table 1 correspond to the estimated evening peak volumes for the year 1990 at the I-291 and Rt-15 interchange. Volumes of Tables 2 and 3 are increased over those of Table 1 in directions east and west or both.

Tables 2 and 3, particularly, show the benefits of differential (method B) over purely synchronous signaling (method C). Dramatic reductions in average transit time and maximum time to leave the system result for the high volume directions at small expense in performance to the low volume directions. Some improvement in the longer transit times also results from the early start feature (method A). The improvement afforded by the early start feature is somewhat marginal, however.

Methods A and D of Table 1 provide an interesting comparison. The fixed cycle of method D (based on traffic volume entering in each direction) is clearly superior to that of method A, which uses differential and early start. In fact, the average transit time for all vehicles is about 84 s with method A and 76 s with method D, a reduction of almost 10 percent. Maximum time to leave the system is also superior for the fixed cycle. The implication of this comparison is not that a fixed cycle is best, since the cycle features must be modified in some way as the input volumes vary. Rather, these results suggest that

1. An early start feature can be helpful (as in Figure 6) even when volumes are too low to require differential and
2. There appears to be a significant benefit in terms of average transit times in using (short-term) average volumes for calculating the features of phase B green. If these features are changed in response to existing queue lengths only, control is less effective.

There are at least two ways of employing short-term average volume information. One is to use an algorithm to design a fixed cycle strategy for any given set of volumes; every 5 to 10 min the cycle parameters may be recomputed on the basis of a new set of average volumes. An easier technique to implement is to modify method A so that it incorporates a more elaborate early start procedure that uses average volume information. For example, suppose phase B green west terminates before phase B green east as in Figure 6. Fifteen seconds after the termination of phase B green west the following calculations and decisions can be made:

1. Determine whether the queue South 01 can be depleted within 30 s after the earliest start of phase B green north (this will require knowledge of queue length

and volume of traffic arriving from the south); if not proceed to step 2; if so start south phase B green immediately and continue for the calculated time required to deplete the queue; start phase B green north 15 s after start of phase A green east; and

2. Use current queue lengths and volumes to determine if phase B green south should be longer than north; if so use the early start feature as in method A; if not use the differential feature of method B without early start.

This set of calculations can be expanded. For example, it may be advantageous to start phase B green south immediately, even if the input queue will not be depleted within 30 s after the earliest start of phase B north. That is, it may be better in the long run, depending on average volumes, to terminate phase B green south with vehicles still in the input lanes rather than to delay the start of phase B green south as may be required in step 2.

In order to implement an algorithm of this type, fairly complex decisions and calculations must be made. Also, short-term average volumes must be estimated and stored. Implementation of the algorithm will, therefore, be most readily accomplished by using a special digital or hybrid computer.

The behavior of vehicles in the circulating and input lanes was about as expected. The average transit times in all circulating lanes is about 16 to 17 s (including delay in crossing the intersection at the end of the lane). The distributions of transit times, with volumes as in Table 1, in lanes South 1, South 2, and South 3 are shown in the following table.

Figure 6. Phase B signal sequence for fixed 80-s cycle designed for volumes of Table 1.

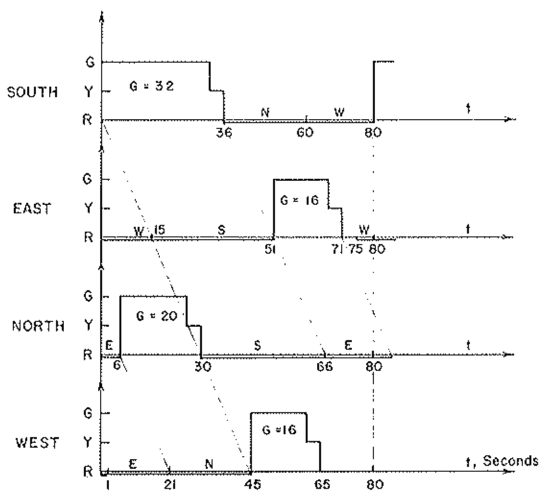


Table 1. Summary of simulation results for projected evening peak input volumes for the year 1990.

Simulation Item	Signal Method	Direction: North (avg 500 veh/h)	South (avg 900 veh/h)	East (avg 400 veh/h)	West (avg 300 veh/h)
Average total transit time, s	A	79.9	90.2	81.8	77.0
	B	79.2	93.8	81.7	76.9
	C	76.1	100.8	76.2	74
	D	80.4	73.3	76.4	75.3
Maximum time to leave system, s	A	130	140	140	140
	B	140	150	130	130
	C	120	170	130	120
	D	130	110	120	130
Maximum contents of input lanes, vehicles	A	10	22	12	6
	B	10	19	10	8
	C	10	19	8	6
	D	11	14	7	6
Percentage vehicles leaving in 110 s	A	89.4	77.8	82.8	87.9
	B	91.8	72.9	87.4	88.8
	C	97.0	59.9	86.4	93.1
	D	92.0	100.0	95.0	93.0
Percentage vehicles leaving in 120 s	A	98.4	92.0	97.1	95.4
	B	96.1	83.7	97.9	98.6
	C	100.0	72.7	98.5	100.0
	D	99.0	100.0	100.0	99.0
Percentage vehicles leaving in 130 s	A	100.0	96.7	99.5	99.0
	B	99.5	93.4	100.0	99.2
	C	100.0	83.4	100.0	100.0
	D	100.0	100.0	100.0	100.0

Table 2. Summary of simulation results for input volume set two.

Simulation Item	Signal Method	Direction: North (avg 500 veh/h)	South (avg 900 veh/h)	East (avg 400 veh/h	West (avg 720 veh/h)
Average total transit time, s	A	81.6	93.3	81.9	88.5
	B	79.2	99.8	80.9	96.0
	C	73.0	105.8	76.3	157.1
Maximum time to leave system, s	A	130	160	130	150
	B	140	170	140	160
	C	120	180	120	260
Maximum contents of input lanes, vehicles	A	11	25	8	14
	B	11	19	9	17
	C	11	19	8	25
Percentage vehicles leaving in 110 s	A	88.9	71.7	86.6	73.8
	B	87.5	58.2	81.0	62.7
	C	95.5	55.2	93.0	12.9
Percentage vehicles leaving in 120 s	A	97.6	79.7	98.8	90.2
	B	95.6	72.3	94.3	78.5
	C	100.0	63.5	100.0	18.6
Percentage vehicles leaving in 130 s	A	100.0	87.4	100.0	95.5
	B	98.5	82.8	99.3	90.7
	C	100.0	76.5	100.0	22.2
Percentage vehicles leaving in 140 s	A	100.0	93.1	100.0	98.8
	B	100.0	92.8	100.0	94.8
	C	100.0	89.7	100.0	27.2

Table 3. Summary of simulation results for input volume set three.

Simulation Item	Signal Method	Direction: North (avg 500 veh/h)	South (avg 900 veh/h)	East (avg 720 veh/h	West (avg 400 veh/h)
Average total transit time, s	A	83.8	94.4	94.5	81.2
	B	82.7	96.2	97.4	88.4
	C	78.9	130.6	132.6	81.0
Maximum time to leave system, s	A	160	160	160	150
	B	140	160	160	140
	C	120	220	220	130
Maximum contents of input lanes, vehicles	A	15	18	18	10
	B	10	18	17	9
	C	11	24	23	8
Percentage vehicles leaving in 110 s	A	83.9	66.8	64.2	80.6
	B	85.3	66.9	69.1	69.2
	C	96.8	21.7	20.2	90.6
Percentage vehicles leaving in 120 s	A	91.9	82.6	81.6	92.7
	B	94.6	78.0	79.7	88.1
	C	100.0	30.8	31.7	99.2
Percentage vehicles leaving in 130 s	A	96.6	91.1	88.7	98.7
	B	99.5	88.8	88.6	97.2
	C	100.0	42.9	39.3	100.0
Percentage vehicles leaving in 140 s	A	97.6	95.4	94.2	99.3
	B	100.0	97.4	94.8	100.0
	C	100.0	55.0	46.3	100.0

Time (s)	Cumulative Percentage (probability distribution x 100)		
	South 1	South 2	South 3
10	0.0	0.0	0.0
20	98.5	95.1	98.1
30	100.0	97.2	100.0
40	100.0	97.2	100.0
50	100.0	100.0	100.0

Thus 95 percent or more of the vehicles did not stop on these lanes (time was less than 20 s). A small number—1 in 70 in South 1, 15 in 290 in South 2, and 4 in 219 in South 3—were required to stop. In all other circulating lanes, the transit time was 30 s or less. Thus, only the slow driver who just manages to enter a circulating lane on an amber light is likely to be caught at the next intersection.

The two tables below indicate behavior in the input lanes for the volumes in Figure 3 or Table 1.

Lane	Average Transit Time (s)	
	Method A	Method D
North 01	48.3	46.6
North 02	46.2	43.7
West 01	48.4	42.8
West 02	42.4	39.7
South 01	58.4	39.4
South 02	56.8	37.2
East 01	51.7	42.5
East 02	47.2	38.6

The first table shows the average transit time for signal methods A and D. Comparison with Table 1 indicates that the improvement in method D over method A in south and east transit times is caused primarily by the reduction in transit times in the input lanes. This, of course, is expected, because circulating lane behavior was essentially the same for all methods.

Time (s)	Cumulative Percentage	
	Signal Method A	Signal Method D
30	8.7	33.4
40	21.3	48.2
50	35.3	66.9
60	48.0	86.0
70	68.9	99.1
80	83.8	100.0
90	92.5	
100	96.5	
110	100.0	

The second table indicates that the maximum time in the input lane South 01 was 80 s for method D, while about 16 percent of the vehicles required longer than 80 s with method A.

SUMMARY

Simulation of left-turning traffic in the I-291 and Rt-15 diamond interchange indicates that the interchange will efficiently service the peak evening traffic volumes projected for the year 1990. Average transit times through the interchange are typically 80 s, with about 50 s required for travel time and 30 s for waiting at the initial intersection. In most cases, vehicles do not need to stop once the circulating lanes are entered. Even the higher volumes of Tables 2 and 3 do not produce serious delays.

The superior performance of method D, which requires average volume data, has suggested further refinements in signaling scheme A, which uses queue length information only. Although implementation of signal control algorithms based on such refinements will likely require a digital or hybrid computer, this is consistent with the trend in signal control at major intersections.

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