A Microcomputer-Based Simulation Program for Intersection Sites During Reconstruction

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The problem of traffic control at intersections during reconstruction is addressed in this paper. This includes not only the appropriate type of control but also evaluation of the effects of geometrics on traffic operations. Evaluation of the alternatives is accomplished through microscopic simulation using an efficient microcomputer-based program specifically developed for this purpose. The program, which runs on the IBM PC, is interactive, menu driven, and has extensive graphic capabilities for easy data entry and better inspection and understanding of the results. It allows for simulation of four-way intersections or T-intersections controlled either by stop signs in all directions or by traffic signals. Because of the modeling used by the program, reliable results can be obtained in a short period of time. Input to the program is entered interactively and includes the number of lanes for each approach, the saturation flow rate for each lane, vehicle clearance times, and vehicle demands. In addition, when traffic signals are simulated, the phasing arrangement and signal timings are entered. Printed outputs for each lane include the number of vehicles serviced and statistics dealing with delays, stops, and queue sizes. In addition to the printed outputs, the program is capable of showing on a graphics screen the simulation of the intersection, including traffic signal indications, queue formation and dissipation, and vehicle arrivals and departures. Design tables and curves are developed for quick determination of the control policy and evaluation of its effectiveness.

The increasing number of intersections undergoing reconstruction in order to upgrade the geometrics and replace outdated control technology has led to the need to estimate the impacts on traffic and to consider a variety of alternative improvements and control strategies that could be implemented during the reconstruction phase. One method of estimating impacts is to perform calculations using one of the many techniques currently available. The *Highway Capacity Manual (1)* provides one source of information for performing such calculations. However, analytical techniques are often time consuming, especially when done manually, and frequently underestimate or overestimate the impacts as a result of geometric or control changes.

In general, more realistic results can be obtained through the use of computer simulation of traffic conditions. Quite often, however, existing simulation programs, such as NETSIM *(2)*, require access to mainframe computers, or more important, the input for such programs is quite extensive and complex, requiring that the user become quite familiar with a sophisticated program before it can be used confidently and effectively. In order to make computer simulation of intersections more appealing and easier to use, an interactive, menu-driven microcomputer program, called INTERCON *(3)*, was sponsored by the Minnesota Department of Transportation (MnDOT) and developed by the University of Minnesota. In addition to the fact that it is microcomputer based, the program is attractive because both entry of data into the program and interpretation of the output are very simple. Graphics displays have been incorporated into the input procedure to provide a visual representation of the options selected, reducing the likelihood of data entry errors. Graphics displays have also been used during the simulation to provide a second-by-second visual depiction of the conditions at the intersection.

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The following is a brief discussion of the modeling, control, and geometric aspects used by the program. Also included are a description of the hardware and software required to operate the program, a summary of the program input and output options, and a brief description of design recommendations, which utilize design curves and tables that were developed using INTERCON simulation results. Finally, the limitations of the program and potential improvements are discussed.

MODELING ASPECTS

Overall modeling strategy is discussed, followed by a description of the modeling techniques used to determine vehicle arrivals and departures.

Microscopic computer simulations of traffic conditions generally fall into one of two categories: time scan, in which the conditions are updated based on time, and event scan, in which the conditions are updated based on the order of certain events.

In a time-scan process, traffic conditions [arrivals, departures, queue sizes (vehicles), queue lengths (feet), locations of vehicles, signal indications] are updated on a fixed time interval basis, generally every 1 sec. This procedure is analogous to taking a snapshot of the system every 1 sec, whether or not anything changed within the system. This procedure is used when it is important to track the locations, speeds, and characteristics of individual vehicles. Although this procedure, in general, provides very precise results, it is also very time consuming and requires a large quantity of computer memory.

In an event-scan process, traffic conditions are updated based on the occurrence of certain events. These events usually consist of vehicle arrivals and departures, and signal indication changes. Because the quantity of detailed information maintained for every vehicle is less than in a time-scan simulation, an event-scan simulation generally requires substantially less computer time and memory. A program that used an event-scan simulation is described by Michalopoulos et al. *(4)* and Michalopoulos and Plum *(5)*. That program was used as the foundation for both the stop sign and signal simulation techniques used in INTERCON.

For the INTERCON program, elements of both time-scan and event-scan simulation are used. Because the simulation can be shown visually on a graphics screen, it is desirable to show the traffic conditions at the intersection at regular time intervals (every 1 sec). However, to conserve time and memory requirements, certain detailed analyses, such as shock-wave propagation within a queue and tracking of vehicles once they have passed through the intersection, are not performed. Consequently, within each 1-sec time frame, an event-scan analysis is performed and all events occurring within that 1 sec are tallied by the computer. At the completion of the 1-sec event scan, all events occurring within that time frame are shown on the graphics screen, although not necessarily in the same order in which they actually occurred.

Vehicle arrivals are assumed to occur randomly within each lane, with a maximum of one vehicle arriving each second. The one-vehicle-per-second rate was used rather than a more normal value (such as 1,800 vehicles per hour) to accommodate situations in which the number of lanes is reduced by construction upstream of the intersection, squeezing vehicles from the eliminated lane into the remaining lane or lanes. The time used for arrival of each vehicle is that at which the vehicle arrives at the back of the queue, or, if no queue is present, at the stop line. For approaches with more than one lane accommodating through traffic, the arrivals of through vehicles are distributed between the lanes so that the total demand in each lane is as balanced as possible with the demand in other lanes on the approach.

Vehicle departures are a function of several parameters entered by the user. The first parameter is the saturation flow rate, which is the maximum rate at which vehicles will cross the stop line if unimpeded by opposing vehicles or the intersection control. The actual departure rate is a function of saturation flow and the lost time that a vehicle will experience. It has been assumed that the first five vehicles in a platoon can be affected by lost time due to driver reaction and acceleration times. Obviously, with stop sign control, all departing vehicles will experience some lost time due to slowing down for the stop sign. The other parameter affecting the actual departure rate is the average gap in the opposing flow, which a driver making a left turn feels is adequate. During the simulation, a uniform distribution ranging from 30 percent below the mean to 30 percent above the mean is used to determine whether a particular gap is acceptable.

Note that INTERCON has been extensively tested against results obtained from the NETSIM simulation program, which over the years has been improved and found to be fairly realistic. The data base included a wide range of volumes and geometric configurations, phasing arrangements and types of control (stop sign, actuated, and pretimed).

CONTROL ASPECTS

Three types of control can be simulated by the INTERCON program: all-way stop-sign control, with a stop sign on each approach; pretimed signal control, with a fixed cycle length, phasing sequence, and phase times; and actuated signal control, with both semiactuated and full-actuated options possible. Because the primary purpose of the program was to evaluate intersections during construction, the actuated signal option assumes that detectors are located only at the stop line. Finally, flagman control is not specifically simulated as it is assumed that it resembles that of actuated controllers.

For this project, MnDOT required that four different phasing arrangements be accommodated by the program when signalized control is selected. The first phasing arrangement is a simple two-phase operation, in which the northbound and southbound movements are serviced concurrently with each other but separate from the eastbound and westbound movements, which also are serviced concurrently with each other. The second phasing arrangement required is a three-phase operation in which the servicing of vehicles in one pair of directions is split. For example, northbound and southbound vehicles may be serviced at the same time, while eastbound vehicles are serviced immediately before or immediately after westbound vehicles. The third required phasing arrangement is a five-phase operation, in which the left-turning traffic in one pair of directions is serviced by an exclusive left-turn phase preceding the phase servicing the through and right-turning movements. The final required phasing arrangement is an eight-phase operation in which left-turning vehicles in all directions are accommodated by an exclusive leading left-turn phase.

To maximize the capabilities of the program while minimizing the additional programming effort, additional phasing options have been added to the program. These additional options include allowing split phasing in both pairs of directions. so that vehicles in all directions can be serviced by an exclusive phase. Another feature added to the program is the allowance of exclusive left-turn phases on any combination of approaches. Consequently, it is possible to select exclusive left-turn phases only for northbound and eastbound traffic, if desired. Finally, the capability of using not only leading but also lagging exclusive left-turn phases has been added to the program.

As a result, the program is capable of simulating practically any phasing arrangement that can be handled by a standard eight-phase dual-ring NEMA controller. Operation of the NEMA controller is described briefly as follows:

```
                       BARRIER
        +-------------------+-------------------+
RING 1  |  Phase 1  Phase 2 |  Phase 3  Phase 4 |
        +-------------------+-------------------+
RING 2  |  Phase 5  Phase 6 |  Phase 7  Phase 8 |
        +-------------------+-------------------+
```

Phases are serviced from left to right. Phases in the same timing ring cannot time concurrently. Phases not in the same timing ring can time concurrently, provided they are on the same side of the barrier. When concurrently timed phases must terminate due to opposing phase calls from across the barrier, the two phases will simultaneously yield right-of-way (signal change to yellow). If the demand from across the barrier requires concurrent phase timing, the right-of-way will be given (signal change to green) simultaneously to the called phases.

In the INTERCON program, Phases 1, 2, 5, and 6 are assigned to the northbound and southbound traffic, and Phases 3, 4, 7, and 8 are assigned to eastbound and westbound traffic. To each possible vehicle movement, a phase designation is assigned. In the INTERCON program, the through and right-turning vehicles are automatically assigned the same phase. If an exclusive left-turn phase is not used to deal with left-turning traffic, the left-turning traffic is also assigned the same phase as the through and right-turning traffic. Not all phases necessarily have a movement assigned to them. Figures 1 and 2 show the movements that can time concurrently at four-approach and T-intersections.

A more complete description of actuated signal control at isolated intersections is given by Staunton *(6)*.

GEOMETRIC ASPECTS

Geometric alternatives that can be simulated using the INTERCON simulation program were identified by MnDOT at the start of the project as those used most frequently during intersection construction and reconstruction.

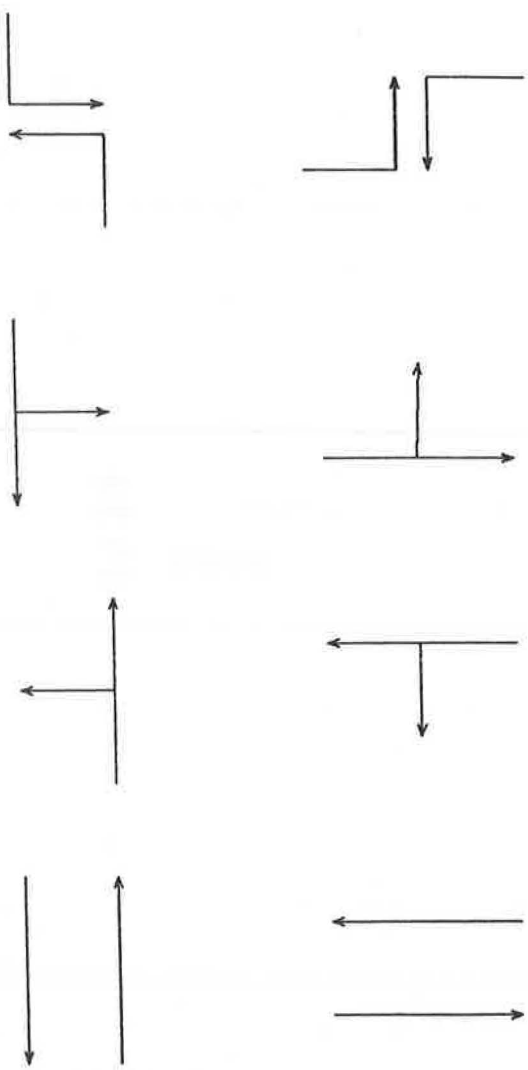

FIGURE 1 Possible signal phasing at four-approach intersections.

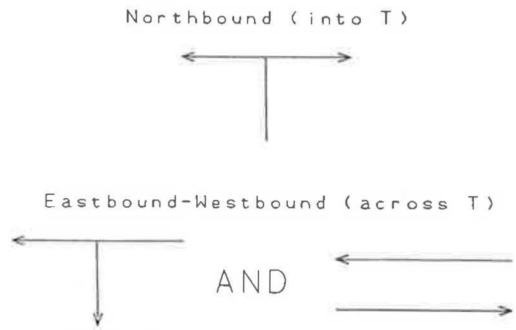

FIGURE 2 Possible signal phasing at T-intersections.

INTERCON can handle either a four-approach intersection or a three-approach intersection (T-intersection). Because the T-intersection can be oriented in any one of the four cardinal directions, there are a total of five possible basic configurations. On each approach, from one to three lanes can be specified, with the following limitations: (a) if stop signs are used to control the intersection or if the intersection is a three-approach (T) intersection, a maximum of only two lanes can be specified on each approach; and (b) on each approach with more than one lane, if left turns are possible from that approach, the program assumes that the leftmost lane is used as an exclusive left-turn lane. The number of lanes and lane use for four-approach and T-intersections are shown in Figures 3 and 4, respectively.

HARDWARE AND SOFTWARE REQUIREMENTS

The minimum hardware and software requirements for running the INTERCON simulation program are listed.

1. IBM personal computer with a minimum of 256k memory.

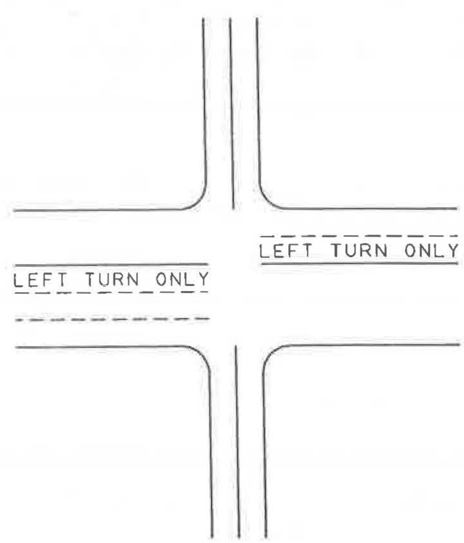

FIGURE 3 Lane possibilities and use for four approaches.

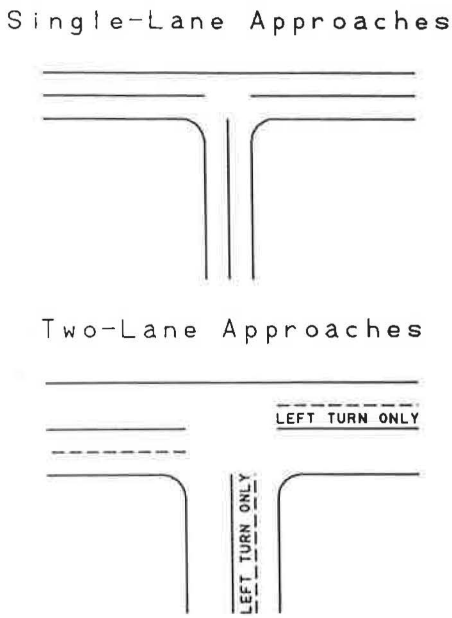

FIGURE 4 Lane possibilities and use for T-intersections.

2. At least one disk drive with a minimum of 320k storage capacity.
3. Monochrome monitor and monochrome display adapter.
4. Color monitor with graphics capability and color graphics display adapter.
5. IBM or Epson dot matrix printer with a minimum of 80 print columns available at 10 characters per inch.
6. PC-DOS or MS-DOS operating system version 2.00 or later.

The program has been running successfully on other microcomputers that are compatible with the IBM PC. The program has also been run successfully on systems with only a single monitor with a graphics adapter, although some of the input assistance provided by various graphics displays has been lost. It should be noted that although the program has operated successfully with other than the hardware just outlined, it has also been tried unsuccessfully on other systems. Consequently, the safest course of action is to use the items exactly as they are tabulated here.

PROGRAM SUMMARY

This section contains a brief summary of the input requirements of the program and the output obtained. Input data for any simulation can be saved on a disk file after data entry is complete. The data can be recalled and easily changed to accommodate future simulations requiring a minimum of input. A more detailed description of the interactive aspects of the program operation is given elsewhere *(3)*.

Program Input

Following is a list of the input required for all simulations, regardless of geometric configuration and type of control.

1. Basic intersection configuration (four way or three way).
2. Type of control (all-way stop sign, pretimed signal, or actuated signal).
3. Number of lanes on each approach.
4. Saturation flow rate for each lane on each approach, in vehicles per hour.
5. Intersection clearance times for each vehicle movement, in seconds. This is the time required for a vehicle making a particular movement to pass through the intersection far enough for a vehicle making a conflicting movement to start to proceed.
6. Initialization time, in minutes. This is a time period preceding the actual simulation during which vehicles are loaded into the system. During the initialization period, no delay, stop, or queue size statistics are maintained, so that the values included in the outputs include only calculations performed during the actual simulation. If an initialization period is not used, the program assumes that there are no vehicles at the intersection when the simulation begins.
7. The number of simulation time slices (periods). The total simulation period can be broken into subintervals of equal duration to allow for demand variations during different times of the day. The number of simulation time slices and the duration of the time slices determine the total simulation period, which can be up to 24 hr.
8. Duration of the individual time periods, in minutes.
9. Vehicle demands, in vehicles per time period. The user enters demand values on each approach for each time period indicated in Item 7. Demand values are also entered for the initialization period, if applicable. The input is the number of left-turning, through, and right-turning vehicles on the approach during the time period.

In addition to the input just described, which is required for all simulations, situations using signal control require inputs dealing with the signal operation and the behavior of drivers in platoons and of drivers making left turns across opposing traffic. These signal-related input items are listed next.

1. Signal phasing arrangement. This item deals with the usage of split or nonsplit phasing, exclusive left-turn phases, and, if left-turn phases are used, whether they precede (lead) or follow (lag) the through movement phases.
2. Signal timing for each phase. Items entered here include green time (for actuated signals, minimum and maximum green times), yellow clearance time, all-red clearance time, extension interval, and whether or not the phase is on minimum recall.
3. Lost times, in seconds. Lost times, the additional time taken by vehicles near the front of a platoon when the signal turns green, are entered for the first five vehicles in the platoon.
4. Average acceptable gap, in seconds, for opposed left-turning traffic. This is the average time headway between through vehicles traveling in the opposite direction that is adequate for a left-turning driver to decide to turn left.

Program Output and Speed

The INTERCON program generates output to the printer, to the monochrome screen, and to the graphics screen.

On the graphics screen, a visual depiction of the simulation

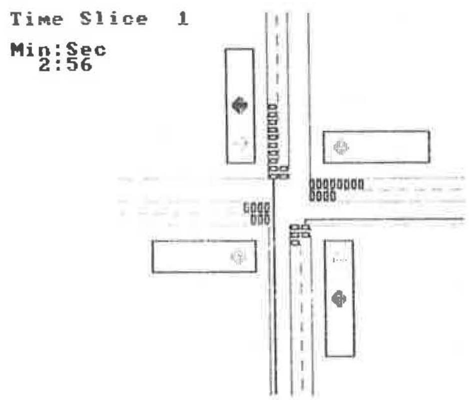

FIGURE 5 Graphics screen display during simulation.

is shown during the simulation process. An example of what the graphics screen display would look like is shown in Figure 5. In the upper left-hand corner of the screen the current time slice being simulated and the current time within that time slice are shown. In the center of the screen is a graphic representation of the intersection, defined by red lines (on the graphics screen). The example shown is a four-approach intersection with two lanes on each approach. Beside each approach, also outlined in red, is the representation of the signal indications to vehicles on the approach. Although the color display has been converted to black and white for this paper, the relative position of the various indications can be seen in the example.

The modeling and programming efficiency allow very satisfactory execution times and data entry. The latter only takes approximately 10 min per intersection for someone familiar with the program; but this time can be expected to triple for beginners. Execution to simulation time is 1:20 when the formation and dissipation of queues along with the movements of individual cars and signal indication are not depicted on the graphics screen and 1:1 otherwise. This latter ratio is intentionally high so that the viewer can follow the performance of the alternative being simulated; if this is not needed for visual inspection of the traffic flow at the intersection, the results of 1-hr simulation can be obtained in only 3 min.

The current display to eastbound and westbound vehicles is a red ball, and the current display to northbound and southbound vehicles is a red arrow to left-turning vehicles, and a green ball to through and right-turning vehicles. The current queue size in each lane can also be determined. Each vehicle is represented by a small yellow rectangle in the lane. The last item shown by the example is an indication of which lanes experienced departures during the current 1 sec of simulation and in which direction those departing vehicles proceeded. Departures are indicated by green lines emanating from the stop line drawn on and then erased from the graphics screen. The example shows a departure from the southbound rightmost (when viewed going in the direction of travel on the approach) lane, which proceeded straight through the intersection, and a northbound departure from the rightmost lane, which turned right and proceeded east.

Output to the monochrome screen during the simulation consists of a minute-by-minute update of the current values for the measures of effectiveness being evaluated. The measures of effectiveness include delay, stops, and current and maximum queue sizes for each approach-lane combination. Similar to what is shown on the graphics screen, the current time slice and time within the current time slice are displayed at the top of the screen.

Three types of output are sent to the printer when the entire simulation has been completed. The first item output to the printer is a summary of the input for the current simulation. This summary is optional and is selected or "deselected" during the input portion of the program. The other two types of output are identical in format except for the title at the top of each page. Printed first is a summary report for the entire simulation. Following this one-page summary report are summary reports for each time slice, allowing the user to evaluate during which time slices potential problems may arise. For both types of summary report, values are output for each approach-lane combination and for the entire intersection. The measures of effectiveness for the values printed are the total number of vehicles that arrived; the total number of vehicles serviced; the total delay, in vehicle hours; the average delay, in seconds per vehicle, based both on the number of vehicles arrived and on the number of vehicles serviced; the total number of stops; the average number of stops per vehicle, again based both on vehicles arrived and on vehicles serviced; the maximum queue size; and the average queue size.

DESIGN RECOMMENDATIONS

The INTERCON program should be used for estimating the performance of the control alternatives at a particular situation so that the best type of control can be determined, perhaps following several simulation runs. The simplicity and speed of the program and the widespread use of personal computers should allow this in most cases. However, if such equipment is not available design curves and tables could be used *(3)*.

This section is intended to be a guide in predicting the best method of control at intersections during construction and reconstruction activities, when use of the INTERCON program is not possible, or for quick reference. Design curves have been developed by performing several hundred simulations using the INTERCON program. A sample design curve and a sample table of results have been included in this section along with explanations of how to interpret them. A complete set of design curves and a complete table of results to provide answers to determining the optimum type of control for a wide range of demands under a variety of geometric conditions are available elsewhere *(3)*.

To minimize the number of simulations performed to derive the curves and tables, certain assumptions have been made. These assumptions were made with the intent that the majority of demand and geometric alternatives would be covered. These assumptions and limitations are listed as follows:

- For simulating T-intersections, it was assumed that the through road is in the north-south direction; that is, there is not a westbound approach so that eastbound traffic has to turn either left or right.
- Because a maximum of two lanes can be specified with stop sign control, only one- and two-lane examples were tabulated and incorporated into the design curves.
- The number of lanes northbound and southbound was assumed to be the same in all cases, and for four-approach

intersections the number of eastbound lanes was assumed to equal the number of westbound lanes.

- In cases where the number of lanes northbound and southbound did not equal the number of lanes eastbound and westbound, the number of lanes northbound and southbound was assumed to be greater.
- Demands were evaluated in increments of 100 vehicles per hour, the northbound demand was equal to the southbound demand, and the eastbound demand was equal to the westbound demand (in four-approach simulations). Only those cases where the northbound demand (major approach) was greater than or equal to the eastbound demand (minor approach) were evaluated.
- On approaches where a through movement and at least one turning movement were possible, each turning movement demand was assumed to be 10 percent of the total approach demand. On approaches where no through movements were possible, 50 percent of the total demand was assumed to turn left and 50 percent was assumed to turn right.
- For signal control, only results obtained from actuated signal control were tabulated. In all cases, pretimed control would yield poorer results. No split phasing was evaluated. For approaches where through movements were possible, an exclusive left-turn phase was used if an exclusive left-turn lane was present. It was assumed that if the left-turn demand was sufficient to require a separate lane, an exclusive phase was also probably justified. The signal timing for each phase consisted of a 7-sec minimum green time, a 90-sec maximum green time, a 3.5-sec yellow time, a 1.0-sec all-red time, and a 4.0-sec extension interval. No phases were assumed to be on recall.
- Lost times for the first five vehicles in the platoon were 2.2, 1.76, 1.32, 0.88, and 0.44 sec, respectively (the defaults used by the program). The average acceptable gap in opposing traffic for left-turning vehicles was 5.5 sec, a value derived from the 1985 *Highway Capacity Manual (1)*.
- Finally, only one simulation was performed for each combination of demand, type of control, and lane configuration in generating the tables shown. Therefore, some of the results, taken on an individual basis, may be suspect due to some unusual condition that may have occurred during a particular simulation. The design curves were generated in order to smooth out some of these anomalies. To accurately determine the results for a particular combination of demand, control, and lane configuration, it is suggested that several simulations be performed using the same parameters. Multiple simulations will yield a range of results and provide a more realistic picture of the average conditions to be expected.

An example of a table of simulation results is given in Table 1. Michalopoulos and Plum give six different tables (three for four-way intersections and three for T-intersections) in another study *(5)*. For each type of intersection the following three lane

TABLE 1 SAMPLE TABLE OF INTERCON RESULTS

	Total	Total	Delay[a]		Stops[a]		Queue Size[a]		Total	Delay[b]		Stops[b]		Queue Size[b]	
	Arrived	Serviced[a]	Total	Average	Total	Average	Max	Average	Serviced[b]	Total	Average	Total	Average	Max	Average
NB/SB 1	10	10	0.01	2.3	10	1.0	1	0.0	9	0.04	15.2	0	0.0	1	0.0
NB/SB 2	90	90	0.07	2.8	90	1.0	2	0.1	89	0.17	6.8	16	0.2	3	0.2
EB/WB	100	100	0.07	2.7	100	1.0	2	0.1	100	0.17	6.3	18	0.1	3	0.2
NB/SB 1	20	20	0.02	2.8	20	1.0	1	0.0	19	0.08	15.0	2	0.1	2	0.1
NB/SB 2	180	179	0.15	3.1	179	1.0	3	0.2	180	0.33	6.6	51	0.3	4	0.3
EB/WB	100	99	0.08	3.1	99	1.0	3	0.1	99	0.25	9.1	20	0.2	4	0.2
NB/SB 1	20	20	0.02	3.3	20	1.0	1	0.0	20	0.10	18.6	1	0.0	2	0.1
NB/SB 2	180	180	0.17	3.4	180	1.0	3	0.2	180	0.55	11.0	70	0.4	5	0.5
EB/WB	200	199	0.20	3.6	199	1.0	3	0.2	199	0.63	11.4	93	0.4	6	0.6
NB/SB 1	30	30	0.02	3.0	30	1.0	1	0.0	30	0.13	16.4	5	0.1	2	0.1
NB/SB 2	270	270	0.28	3.8	270	1.0	4	0.3	269	0.59	7.9	103	0.4	6	0.6
EB/WB	100	100	0.09	3.4	100	1.0	2	0.1	99	0.36	13.2	30	0.3	6	0.3
NB/SB 1	30	30	0.03	3.7	30	1.0	2	0.0	30	0.25	30.5	7	0.2	3	0.2
NB/SB 2	270	270	0.32	4.4	270	1.0	3	0.3	268	1.06	14.3	149	0.5	7	1.0
EB/WB	200	199	0.26	4.8	199	1.0	4	0.3	199	0.87	15.7	105	0.5	8	0.8
NB/SB 1	30	30	0.03	3.8	30	1.0	2	0.0	30	0.32	38.5	8	0.2	3	0.3
NB/SB 2	270	270	0.38	5.2	270	1.0	4	0.4	270	1.60	21.4	172	0.6	8	1.6
EB/WB	300	299	0.49	5.9	301	1.0	5	0.5	300	1.36	16.3	191	0.6	8	1.3
NB/SB 1	40	39	0.03	3.4	39	1.0	2	0.0	40	0.22	19.5	8	0.2	4	0.2
NB/SB 2	360	360	0.46	4.7	361	1.0	5	0.4	360	0.96	9.7	169	0.5	9	0.9
EB/WB	100	100	0.10	3.6	100	1.0	2	0.1	100	0.45	16.4	34	0.3	5	0.4
NB/SB 1	40	40	0.05	4.1	40	1.0	2	0.0	40	0.38	34.3	12	0.3	3	0.3
NB/SB 2	360	360	0.58	5.8	361	1.0	5	0.5	360	1.72	17.3	226	0.6	9	1.7
EB/WB	200	200	0.28	5.1	200	1.0	3	0.3	197	1.04	19.0	114	0.6	7	1.0
NB/SB 1	40	40	0.05	4.2	40	1.0	2	0.0	40	0.54	49.3	16	0.3	4	0.5
NB/SB 2	360	359	0.76	7.7	367	1.0	6	0.8	359	2.75	27.6	262	0.7	15	2.7
EB/WB	300	300	0.57	6.9	301	1.0	5	0.6	299	2.06	24.8	216	0.7	11	2.0
NB/SB 1	40	40	0.06	5.4	40	1.0	2	0.0	39	0.69	63.9	19	0.5	4	0.7
NB/SB 2	360	360	0.87	8.7	367	1.0	7	0.8	348	3.89	40.2	293	0.8	16	3.9
EB/WB	400	400	1.21	10.9	438	1.1	8	1.2	396	3.76	34.2	337	0.8	19	3.7

NOTE: Values apply to each approach. Total arrived/serviced and queue size, in vehicles. Total delay, in vehicle hours; average delay, in seconds per vehicle.
[a]Stop sign control.
[b]Actuated sign control.

combinations were simulated: one lane per approach in all directions, two lanes per approach in the major approach directions (northbound and southbound) and one lane per approach in the minor approach directions (eastbound and westbound), and two lanes per approach in all directions. Simulation results for both stop sign control and signal control have been placed side-by-side for a quick comparison of the two methods of control. The results include the number of vehicles serviced, total and average delay, total and average number of stops, and the maximum and average queue sizes.

To utilize the tables, it is first necessary to select the proper table. As stated earlier, a separate table exists for each combination of general configuration (four-way or T-intersection) and lane configuration (one lane on all approaches, two lanes on the major approaches and one lane on the minor approaches, and two lanes on all approaches). The next step is to find the group of results that corresponds to the major approach demand. To do this, look at the values under the "Total Arrived" column in the table and find where the northbound/southbound values approximate the major approach demand and the eastbound/westbound values approximate the minor approach demand. If an approach consists of two lanes, it is necessary to add the values for Lane 1 and Lane 2 together (identified as NB/SB 1 and NB/SB 2 for the major approaches), where Lane 1 is the leftmost lane and lane numbers increase to the right. The results for each lane or approach can then be obtained from the group in which the major approach demands correspond to the northbound and southbound arrivals, and the minor approach demands correspond to the eastbound and westbound arrivals. For instance, in the sample table shown, it is assumed that the major approaches have two lanes per approach, and the minor approaches have one lane per approach. If the major approach demands are 400 vehicles per hour per approach and the minor approach demands are 200 vehicles per hour per approach, then the average delay expected in the left-turn lane (Lane 1) on the major approaches is 4.1 sec per vehicle with stop sign control and 34.3 sec per vehicle with actuated signal control.

A complete set of design curves intended to help the user to rapidly determine which method of control is appropriate for a variety of combinations of demands and geometric configurations is provided elsewhere *(3)*. Total intersection delay is the sole criterion used in determining the optimum type of control in each case. Figure 6 is an example of one of the design curves obtained from the INTERCON simulations. This design curve was selected because it shows all of the elements that may be encountered when using any of the other design curves. To use the design curve, draw a horizontal line through the vertical axis at the point where the value on the vertical axis equals the major approach demand. Next draw a vertical line through the horizontal axis at the point where the value on the horizontal axis equals the minor approach demand. The point of intersection of the two lines drawn will fall within one of the four labeled areas. If the point falls in the area labeled Not Simu-

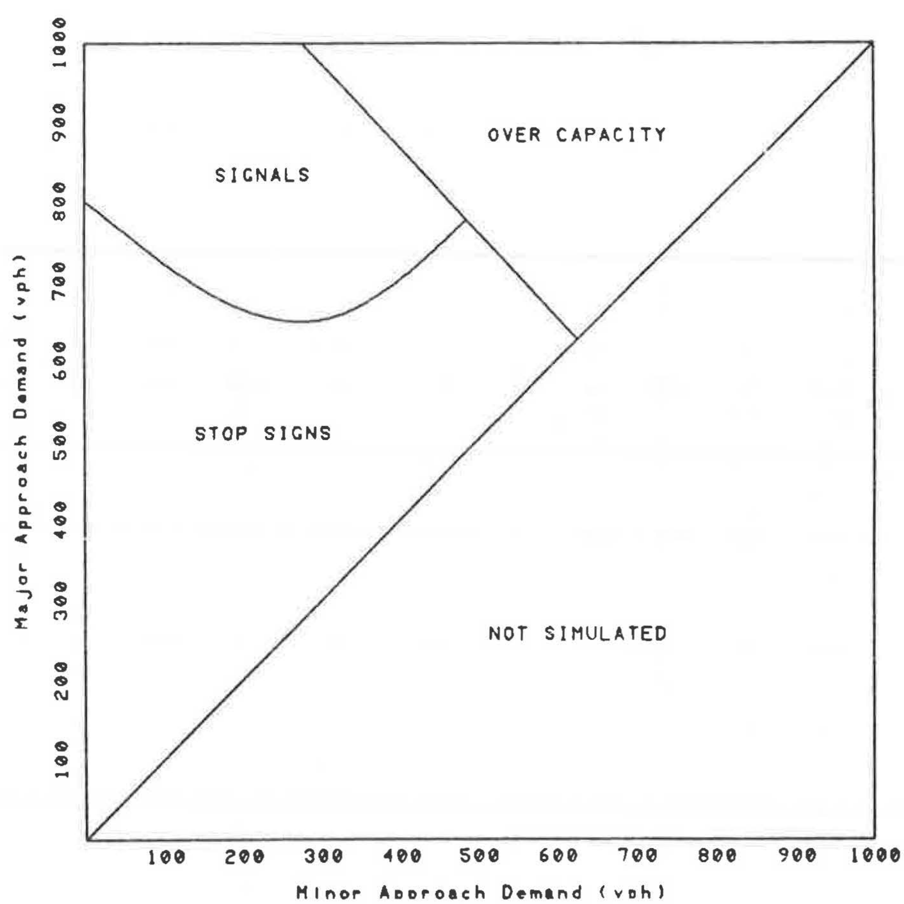

FIGURE 6 Sample design curve for type of control.

lated, that particular combination of demands and geometric configuration was not simulated. In this case it is recommended that the program be used to simulate the conditions for both stop sign and signal control in order to make a control determination. If the point of intersection falls in the area labeled Stop Signs, stop sign control will yield lower delays than actuated signal control. If the point of intersection falls in the area labeled Signals, actuated signal control will yield lower delays than stop sign control. Finally, if the point of intersection falls within the area labeled Over Capacity, less than 90 percent of the demands can be accommodated by any type of control for the selected combination of demands and geometric configuration. In such a case, the user must decide whether the resulting situation would be acceptable; demands that are greater than capacity may be acceptable for short periods of time during the day if the type of control selected can adequately accommodate the demands during the remainder of the day.

In general, the simulations performed revealed that stop sign control caused lower delays than signal control in lower-demand situations but higher delays in higher-demand situations. Although this finding is hardly surprising, another finding was not nearly so intuitively evident: for cases in which all approaches consisted of one lane, stop sign control yields lower delays than signal control for all demand combinations tested. The primary reason that signal control did not perform well even under higher-demand conditions is that left-turning vehicles (10 percent of the total demand) blocked following vehicles for significant periods of time while waiting for gaps in opposing flow. On the other hand, with stop sign control, left-turning vehicles were not treated significantly different from any other vehicles, being serviced primarily based on arrival time at the stop line.

CONCLUSIONS AND RECOMMENDATIONS

The INTERCON intersection simulation program provides a fast, easy, and reliable method for evaluating current or future conditions at intersections undergoing construction or reconstruction. In addition, the tables and design curves developed using INTERCON provide a convenient means of estimating the impacts and determining the best form of traffic control for a variety of geometric alternatives in construction environments without resorting to employing the program itself.

INTERCON is useful for its intended purpose; that is, evaluating intersection operation during construction activities. However, because a reliable working program in a relatively short period of time was needed, certain limitations on the program's capabilities had to be imposed. These limitations, because they are oriented primarily to construction sites, prevent INTERCON from becoming a program capable of simulating nearly all intersections, rather than just those undergoing construction.

To expand the scope of INTERCON's capabilities, certain additions must be made to the program to reduce or eliminate the existing limitations. These additions are outlined here.

First, in addition to all-way stop sign control, simulation of one-way stop sign control for T-intersection and two-way stop sign control for four-approach intersections should be incorporated into the program. In the Twin Cities of Minneapolis and St. Paul at least, and probably statewide and nationwide as well, fewer intersections are controlled by all-way stop sign control than by some less restrictive use of stop signs.

Second, the geometric capabilities should be increased. By increasing the number of lanes that can be simulated on any approach, the number of intersections that can be evaluated will also increase. In addition to increasing the number of lanes on an approach, different type of channelization should be incorporated into the program. Such channelization may include exclusive right-turn slip ramps, exclusive right-turn lanes, multiple exclusive turn lanes (e.g., dual left-turn lanes), and shared lanes in which more than one type of movement can be made from a lane, specifically shared through or left-turn lanes.

Third, data entry and evaluation of the effects of different vehicle types, such as trucks and buses, on the intersection operation must be allowed.

Fourth, modeling should include platooned arrivals to estimate the impacts of evaluating a signalized intersection upstream of the current intersection.

Finally, the capabilities of traffic signal control must be increased. Improvements in this area may include: simulation of right turns on red; a combination of protected and permissive phasing for left-turning vehicles; right-turn phasing; detector placement at points on an approach other than at the stop line; multiple detectors in the same approach lane; assignment of functions to individual detectors (delays, call only, extend only, call and extend); data entry of coordination parameters; and the addition of volume-density operation to controller inputs.

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