SIMULATION OF FLASHING SIGNAL OPERATIONS

by

Luis E. Moreno
Graduate Assistant

and

Michael J. Demetsky
Faculty Research Scientist

(The opinions, findings, and conclusions expressed in this report are those of the authors and not necessarily those of the sponsoring agencies.)

Virginia Highway & Transportation Research Council
(A Cooperative Organization Sponsored Jointly by the Virginia Department of Highways & Transportation and the University of Virginia)

In Cooperation with the U. S. Department of Transportation
Federal Highway Administration

Charlottesville, Virginia

September 1982
VHTRC 83-R11

TRAFFIC RESEARCH ADVISORY COMMITTEE

L. C. TAYLOR II, Chairman, District Traffic Engineer, VDH&T

J. B. DIAMOND, District Traffic Engineer, Staunton, Virginia

J. E. GALLOWAY, JR., Assistant Materials Engineer, VDH&T

D. C. HARRIS, TSM & Programs Engineer, FHWA

C. O. LEIGH, Maintenance Engineer, VDH&T

W. C. NELSON, JR., Assistant Traffic & Safety Engineer, VDH&T

H. E. PATTERSON, Senior Traffic Engineer, Dept. of Public Works, Norfolk, Virginia

R. L. PERRY, Assistant Transportation Planning Engineer, VDH&T

F. D. SHEPARD, Research Scientist, VH&TRC

ABSTRACT

Various guidelines that have been proposed for the operation of traffic signals in the flashing mode were reviewed. The use of existing traffic simulation procedures to evaluate flashing signals was examined and a study methodology for simulating and evaluating potential flashing signal schemes was developed. A case study is described in which the performance of existing signal settings versus flashing signal strategies was tested for different levels of main street and side street traffic volumes. The study showed that the main street flow improves with flashing signals in its favor under all circumstances, while increased volumes typically create longer delays at the side street. Major and side street traffic volumes are recommended as the focus of guidelines for using flashing signals during peak flow periods.

SIMULATION OF FLASHING SIGNAL OPERATIONS

by

Luis E. Moreno
Graduate Assistant

and

Michael J. Demetsky
Faculty Research Engineer

INTRODUCTION

Nationally, as a means of improving the efficiency of traffic flow, consideration has been given to the operation of traffic signals in the flashing mode at selected intersections. Implementation of this strategy has been limited, and universal criteria for operating traffic signals in a flashing mode under given circumstances have not been developed.(1)

One application of the use of flashing signals that has been widely discussed but seldom used is for the control of peak-hour traffic at locations where the two-way main street volume is greater than 200 vehicles per hour (vph) and the ratio of the main street to the side street volume is greater than 3.(1) Traffic signals are often placed on flashing operations when low overall traffic volumes are experienced, as in the early morning hours. Warrants for changing signal control between regular and flashing operations are provided in the Manual on Uniform Traffic Control Devices (MUTCD), and are based on the following considerations:

> When for a period of four or more consecutive hours any traffic volume drops to 50% or less of the stated volume warrants, it is desirable that flashing operation be substituted for the conventional operation for the duration of such period.(2)

At present, many arterial highways operate very inefficiently, especially during work-peak periods, and undue delays to commuters result from traffic signals at junctions of access to local businesses and shopping centers which experience peak traffic at other times.

In most cases, field experimentation with traffic controls is impossible due to limitations of time and cost and the effects on motorists. Simulation modeling, on the other hand, gives the engineer the ability to choose among alternatives before committing financial resources to the implementation of a control strategy in the field.

SCOPE

This report first summarizes the state of the practice of setting traffic signals in the flashing mode. Various guidelines that have been proposed for the operation of flashing traffic signals are listed.

A case study site was selected to evaluate, via simulation, the performance of existing signal settings versus various flashing signal strategies. The ability of the NETSIM model to accomplish the desired simulation was evaluated along with the performance of the alternative signal plans.

Recommendations are given citing conditions where traffic engineers should consider operating traffic signals in the flashing mode.

For the purpose of this study, it was assumed that the effect of a flashing signal control on accidents is similar to that of a two-way stop sign. This is an important statement because accident measures were not obtainable for this investigation so that inferences on the influence of flashing signals and accidents had to be drawn from experiences with two-way stop signs. A recent study for the NCHRP concluded that there was no statistically significant relationship between control device (two-way stop sign vs. signal) and overall accident cost. The two-way stop sign generally produced fewer but more severe accidents than did the signal control.[(3)]

CURRENT PRACTICE

While the <u>MUTCD</u> provides no strict guidelines for operating traffic signals in the flashing mode, there are reports of cases where traffic engineers have implemented flashing signal strategies during periods where there were volumes below the levels specified in the traffic signal warrants. Research on the subject has been conducted and local warrants recommended.

The studies described in Appendix A have demonstrated that traffic signals produce greater total intersection delay than two-way stop signs. It has been found that side street delay is reduced by a properly timed traffic signal only when the volume associated with it is relatively high. These findings suggested minimum volumes at 100 vph for a one-lane approach and 150 vph for two-lane approaches.[(4)] When the side street volume is lower, it was demonstrated that side street delay and total intersection delay will increase; therefore a flashing operation is recommended below such volume levels. Another study suggested that the main street to side street volume ratio should be 3.0 or more before flashing operation is implemented.[1] Hydrocarbons and oxides of nitrogen emissions meet the same 3.0 criterion found for fuel consumption. Carbon monoxide emissions due to idle time are somewhat higher.

Table 1 summarizes the criteria found in the literature for the operation of traffic signals in the flashing mode. All but Box's peak-hour-delay warrant are associated with prolonged drops in some specified traffic volume. The 1961 edition of the MUTCD and KLD & Associates recommend a period of four or more hours before switching to flashing operations. Benioff and Smith do not clearly state how long the drop in volume should be before flashing operation is considered. The information provided suggested a period of four hours or more for the Benioff study and possibly two hours for the Wilbur Smith study. The latter considers regular operation only for the pronounced peak period associated with the daily start or end of operation of a major traffic generator.

The Box peak-hour-delay warrant is based on the waiting time for those vehicles at the side street approaches. At a constant average delay (D/V), only a lower volume for the side street would reduce the vehicle-hours delay for that approach.

All the above show that there is potential for enhancing the efficiency of traffic flows by utilizing the flashing mode when side street volumes are low. These low volumes may occur during the main street peak hour at locations like shopping center entrances and industrial driveways.

Table 1

Suggested Criteria for the Operation of Traffic Signals in the Flashing Mode

Source	Criteria for Flashing Operation
MUTCD[2]	1. When traffic volumes drop below 50% of the minimum volumes stated in the Minimum Vehicular Volume Warrant for four or more consecutive hours.
	2. Traffic actuated signals should not flash unless an unusual circumstance occurs.
	3. Flashing operation should be restricted to no more than three separate periods during each day.
Paul C. Box & Assoc.[5]	1. During those periods of at least two hours in which the delay caused by a stop sign is less than 60% of that suggested in the peak-hour-delay warrant.

Table 1 (cont.)

Source	Criteria for Flashing Operation
KLD & Assoc.[3]	1. To flash any fixed-time signal installation when this study's vehicular volume warrant is not satisfied during periods of at least four consecutive hours.
	2. To flash the traffic-actuated signals installed at school crossings during all times other than school crossing hours.
Wilbur Smith & Assoc.[4]	1. Flashing operation is recommended when the side street volume drops below some specified volume. These guidelines are for side streets (driveways) that exhibit pronounced peak periods due to the operations schedule of the associated development.
Benioff et al. (TJKM)[1]	1. Flashing yellow/red operation is suggested when two-way traffic volumes on the main street are below 200 vph.
	2. For traffic volumes over 200 vph, flashing yellow/red is suggested if the ratio of main street to side street volume is greater than 3.0.

NOTE: See Appendix A for description of the above criteria.

SIMULATION STUDY METHODOLOGY

Model Specifications

Although the aforementioned guidelines do suggest cases where traffic signals can be placed in the flashing mode to reduce delays, energy consumption, and atmospheric emissions, there is sufficient uncertainty that a careful site analysis is needed in most cases to estimate the impacts of the plan. The most promising technique available to the traffic engineer for this purpose is a traffic simulation model.[6] By using the simulation model and carefully analyzing the statistical output, he can compare the operational effects of flashing signal strategies with those of other plans. Thus, if the guidelines suggest that flashing signals may be appropriate for an urban arterial at specified points, a procedure for projecting the results will complement the guidelines to provide a comprehensive planning method.

Various network simulation models are available, and some have been extensively tested and validated for specified applications. Three of the most commonly used models are TRANSYT, SIGOP II, and NETSIM. These are discussed in Appendix B and only conclusions are presented here.[7,8,9,10]

One of the objectives of the research was to simulate traffic flow along an arterial street with traffic signals operating in the flashing mode. Therefore, it was necessary that the strategies used simulate signals in the flashing mode and provide output data on the measures of effectiveness under investigation.

Model Selection

No network traffic simulation model available includes a subroutine for the simulation of traffic signals in the flashing operation mode. However, flashing operation acts like a two-way stop sign when signals flash yellow/red, or a 4-way stop sign when signals flash red/red. Therefore, a model that could adequately represent the stop sign operation was used for this research.

The TRANSYT model handles the stop sign by merely reducing the discharge according to the opposing traffic volume. This performance does not agree with the traffic regulations for stop signs. SIGOP II, as TRANSYT, was designed for the optimization of signalized intersections. Unsignalized intersections cannot be represented with this model, unless they are represented as source/sink nodes or as a "dummy" signal; therefore, stop signs are not accepted by this model. Both SIGOP II and TRANSYT outputs include measures of delay and vehicle stops, but produce no output on fuel consumption and vehicle emissions.

On the other hand, the NETSIM model was designed as an evaluation tool. It can represent a variety of intersection controls, including the stop and yield signs; fixed-time traffic signals, operating either independently or as part of a coordinated system; vehicle-actuated signals; or more complex signal systems operating under dynamic, real-time control. Because these capabilities make the model capable of simulating signals in the flashing operation mode it was selected for this study. The output it provides includes many parameters of the performance of the simulated network. In addition to various measures of delay, vehicle stops, and travel time, the fuel consumption and vehicle emissions, which are relevant here, are estimated.

Selection of the Case Study

The U. S. Route 29 north corridor in the Charlottesville-Albemarle metropolitan area was selected as the study location. This arterial connects the University of Virginia with the shopping centers located north of the city through 3.5 miles (5.6 km) of industrial and commercial facilities, most of them with direct access to the arterial. A link-and-node diagram of this highway is shown in Figure 1. Thirty internal nodes (seven of which correspond to the ramps that connect the Route 250 By-pass with Route 29 north, and 40 dummy nodes are included. The dummy nodes are required to evaluate the performance of the side street links.* (The model accumulates statistics only for internal nodes.) There are 84 internal links and 40 entry links in this "ladder" network. Also, four pseudo-links are present: Lambeth parking lot, Carruther's Hall south entrance, Holiday Inn's south entrance, and Woodland Day School Road.

Data Collection

The NETSIM model requires the following input data, which must be entered into the model to define the network to be simulated.(10)

- Intra-link target speeds
- Intersection discharge rates
- Input flow rates (vph)
- Frequency of rare events
- Intersection turning movements
- Bus system data
- Traffic composition (vehicle types)
- Pedestrian flows and delays
- Network geometry and special channelization
- Signal timing and phasing
- Detector location and type

---

*See Appendix C for an explanation of the dummy node.

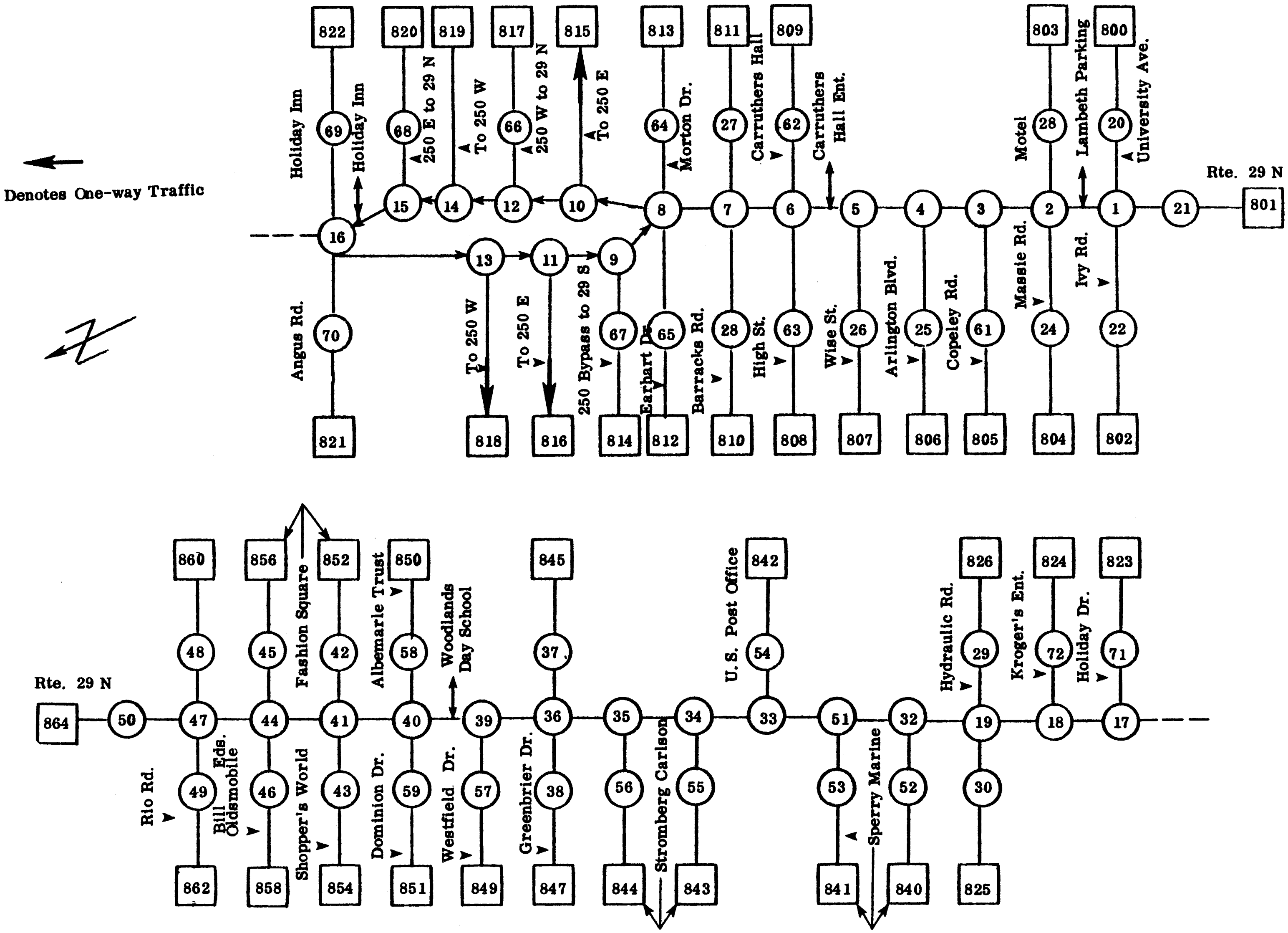


Figure 1. Link-and-node diagram for Route 29 North in Charlottesville.

Data collection was a major task for the simulation, with much of the data being provided by the Virginia Department of Highways and Transportation's Culpeper District Office and by the city of Charlottesville. The remaining data were collected by the Council as a part of this study. Since it was impossible to simultaneously obtain traffic data for the whole network because of economic and personnel limitations, it was necessary to utilize traffic counts that had been made at different dates. These data were adjusted as accurately as possible to represent the traffic flow conditions to be simulated and used for computer input. The input flow rates for the entry links are shown in Table 2.

Appendix C describes the process of translating the field data into the format required for input to the computer, as well as the particular problems with the model and its documentation that had to be overcome prior to obtaining a successful simulation.

Table 2

Entry Link Volumes

Link	Flow Rate (veh/hr)	Link	Flow Rate (veh/hr)
(800, 20)	482	(826, 29)	938
(801, 21)	802	(847, 38)	419
(802, 22)	476	(845, 37)	63
(803, 23)	17	(852, 42)	204
(804, 24)	253	(854, 43)	214
(805, 61)	10	(856, 45)	169
(806, 25)	394	(858, 46)	60
(807, 26)	166	(840, 52)	30
(808, 63)	93	(841, 53)	21
(809, 62)	111	(843, 55)	53
(810, 28)	768	(844, 56)	121
(811, 27)	672	(849, 57)	64
(812, 65)	53	(860, 48)	572
(813, 64)	43	(862, 49)	583
(823, 71)	29	(864, 50)	930
(814, 67)	196	(850, 58)	150
(817, 66)	164	(851, 59)	110
(820, 68)	385	(842, 54)	162
(821, 70)	292	(1, 2)	-18
(822, 69)	8	(5, 6)	7
(824, 72)	158	(15, 16)	-61
(825, 30)	720	(36, 40)	- 4

Simulation Method

Because of the excessive computer costs incurred in simulating the test system (an average of $600 per run), the simulations were run to represent 5 minutes of real time. For test cases, various simulations with different volume levels were attempted. The first run was made with the actual conditions for the traffic signals with the afternoon peak hour volumes. Using the same traffic volumes, a simulation was performed using flashing signals at the following intersections or entrances: Wise Street (5), Shopper's World (41), and Fashion Square Mall (44). This was accomplished by the use of side street stop signs in the NETSIM codification.

Since the intention of the study was to investigate the flashing operation of signals at different volume levels, further simulations were performed. These included runs at 50% and 150% of the afternoon peak-hour volumes. Also, another simulation was made in which the traffic volumes at the three signalized major shopping area entrances were those for the morning peak hour. This was done to check the intersection's performance when the side street volume was very low and the arterial volume at its peak.

When simulations at double- and triple-peak afternoon volume levels were attempted, they were impeded by limitations of the computer model. Efforts to overcome such limitations were unsuccessful.

The network occupancy capability of NETSIM is only 1,600 vehicles. When the afternoon peak-hour volume was doubled, this maximum occupancy was attained after 51 seconds of simulation, and then simulation was aborted. When the volume was tripled, simulation was aborted before starting; equilibrium could not be obtained at such volumes with the occupancy constraints intrinsic to the program.

The occupancy limitations of the model can be increased, but this will increase computer time considerably. For this case study it was attempted. Personnel from KLD & Associates, consultants for the NETSIM computer model, were contacted. They commented that an increase in the model occupancy capability would not be worthwhile because of the already congested entry links. A complete modification of the network was suggested as an alternative. This was not attempted because of time limitations. Also, the scope of the investigation was considered to have been met with the volume levels already simulated.

RESULTS

Prior to the analysis of the flashing signals the accuracy of the simulated traffic volumes was examined. The simulated volumes of various locations were compared with the volumes submitted as input to the program. It was found that most of the volumes were satisfactorily simulated (with 10% difference). The computer output volumes at the intersection of Route 29 north with Barracks Road were low compared with the actual counts. The main reason for this was the limitation of NETSIM related to the coordination of dual-ring traffic signal controllers. The actual timing and phasing for this signal was not coded because NETSIM would not accept it. When the improvised flashing operation was simulated using stop signs for the approaches that flash red, the stops per vehicle (S/V) at some of them were lower than 1.0. This finding is an indication that stop sign operation is not correctly reproduced by NETSIM. All vehicles that face a stop sign (or a flashing red signal) should be shown to stop before proceeding through the intersection.

Corridor Impacts

The results obtained for the afternoon peak-hour volume, for 50% and 150% of such peak volume, and for the traffic volume during the morning peak at the three signalized major shopping area entrances are shown in Tables 3 through 6, respectively. These tables include the MOE's estimated by NETSIM for each of the runs.

Afternoon Peak-Hour Volume

The results contained in Table 3 for the afternoon peak-hour volume show a slight improvement in the Route 29 north corridor performance when the signals at the three major shopping area entrances were changed to flashing operation. An analysis of the performance of the signalized intersections showed that at the locations changed to flashing operation, the total intersection delay (TID) and the average delay per vehicle (D/V) were decreased, and that the overall performance there was better. The D/V for side streets at these intersections increased for some approaches and decreased for others, depending on the intersection geometrics, traffic volume, and conflicts in turning movements. Wise Street forms a "T" intersection with Route 29 north; therefore no through traffic impedes the left-turning movements. This helped to reduce the delay there.

Table 3

Measures of Effectiveness for Flashing and Regular Operation of Traffic Signals at Afternoon Peak-Hour Volume

Measure of Effectiveness*	Regular Operation	Flashing Operation	Change	% Change
Vehicle miles	725.36	742.71	+ 17.35	+ 2.39
Vehicle trips	841.00	848.00	+ 7.00	+ 0.83
Vehicle minutes	2,721.60	2,623.70	- 97.90	- 3.60
Stops/vehicle (avg.)	2.06	2.03	- 0.03	- 1.46
Average speed (mph)	15.99	16.98	+ 0.99	+ 6.19
Average delay/vehicle (sec./veh.)	113.97	105.22	- 8.75	- 7.68
Total delay (veh.-min.)	1,597.50	1,487.10	-110.40	- 6.91
Delay/veh. mile (min./veh. mi.)	2.20	2.00	- 0.20	- 9.09
Fuel consumption (mpg)	10.02	10.30	+ 0.28	+ 2.79
Veh. emissions (gm./mile)				
HC	3.94	3.80	- 0.14	- 3.55
CO	67.59	64.68	- 2.91	- 4.31
NOX	6.82	6.72	- 0.10	- 1.47

*NOTE: 1 mi. = 1.6 km.

1190

Table 4

Measures of Effectiveness for Flashing and Regular Operation of Traffic Signals at 50% Increase in Afternoon Peak Volume

Measure of Effectiveness*	Regular Operation	Flashing Operation	Change	% Change
Vehicle miles	867.58	872.62	+ 5.04	+ 0.58
Vehicle trips	1,167.00	1,142.00	- 25.00	- 2.14
Vehicle minutes	5,371.20	4,984.30	-386.90	- 7.20
Stops/vehicle (avg.)	2.62	2.18	- 0.44	-16.79
Average speed (mph)	9.69	10.50	+ 0.81	+ 8.36
Average delay/vehicle (sec./veh.)	206.64	190.81	- 15.83	- 7.66
Total delay (veh.-min.)	4,019.10	3,631.80	-387.30	- 9.64
Delay/veh. mile (min./veh. mi.)	4.63	4.16	- 0.47	-10.15
Fuel consumption (mpg)	7.31	7.77	+ 0.46	+ 6.29
Veh. emissions (gm./mile)				
HC	5.52	5.17	- 0.35	- 6.34
CO	101.55	94.60	- 6.95	- 6.84
NOX	7.55	7.28	- 0.27	- 3.58

*NOTE: 1 mi. = 1.6 km.

Table 5

Measures of Effectiveness for Flashing and Regular Operation of Traffic Signals at 50% Decrease in Afternoon Peak Volume

Measure of Effectiveness*	Regular Operation	Flashing Operation	Change	% Change
Vehicle miles	401.40	407.19	+ 5.79	+ 1.44
Vehicle trips	445.00	457.00	+ 12.00	+ 2.70
Vehicle minutes	1,066.10	1,039.20	- 26.90	- 2.52
Stops/vehicle (avg.)	1.67	1.52	- 0.15	- 8.98
Average speed (mph)	22.59	23.51	+ 0.92	+ 4.07
Average delay/vehicle (sec./veh.)	62.45	56.07	- 6.38	- 10.22
Total delay (veh.-min.)	463.20	427.10	- 36.10	- 7.79
Delay/veh. mile (min./veh. mi.)	1.15	1.05	- 0.10	- 8.70
Fuel consumption (mpg)	12.02	12.51	+ 0.49	+ 4.08
Veh. emissions (gm./mile)				
HC	3.14	2.95	- 0.19	- 6.05
CO	50.95	47.12	- 3.83	- 7.52
NOX	6.37	6.10	- 0.27	- 4.24

*NOTE: 1 mi. = 1.6 km.

Table 6

Measures of Effectiveness for Flashing and Regular Operation of Traffic Signals Volumes at Nodes 5, 41, and 44 During Morning Peak Volume

Measure of Effectiveness*	Regular Operation	Flashing Operation	Change	% Change
Vehicle miles	700.81	704.42	+ 3.61	+ 0.52
Vehicle trips	835.00	817.00	- 18.00	- 2.16
Vehicle minutes	2,423.20	2,436.00	+ 12.80	+ 0.53
Stops/vehicle (avg.)	1.90	1.84	- 0.06	- 3.16
Average speed (mph)	17.35	17.35	± 0.00	± 0.00
Average delay/vehicle (sec./veh.)	97.52	100.43	+ 2.91	+ 2.98
Total delay (veh.-min.)	1,357.10	1,367.50	+ 10.40	+ 0.77
Delay/veh. mile (min./veh. mi.)	1.94	1.94	± 0.00	± 0.00
Fuel consumption (mpg)	10.30	10.51	+ 0.21	+ 2.04
Veh. emissions (gm./mile)				
HC	3.79	3.70	- 0.09	- 2.37
CO	64.49	63.25	- 1.24	- 1.92
NOX	6.79	6.58	- 0.21	- 3.09

*NOTE: 1 mi. = 1.6 km.

At the south entrance to Fashion Square (node 41), the percentage of traffic that executes a left-turning movement (94%) is high and crosses five lanes. Also, the arterial traffic volume is high. Therefore the D/V increased at this link. Link 46-44 (Bill Edward's Oldsmobile) has only one lane for all turning movements, and a slight increase in delay occurred there. All links but the southern entrance to Fashion Square had a D/V lower than the 25-second maximum recommended by KLD & Associates. The D/V at the arterial links of the three intersections having a simulated flashing operation was also reduced.

The performance at almost all signalized intersections was improved. The arterial traffic flow was better because of reductions in the average delay, and total delay it experienced. The lowering of the total delay and number of vehicle stops reduced the fuel consumption per vehicle-mile of travel as more energy is consumed when a vehicle stops than during idling delay. "A vehicle stop is equivalent to one minute of idling delay in its energy use, even though a vehicle stop without idling time causes less than one minute of delay."[11]

Fifty Percent Increase in Afternoon Peak Volume

When the afternoon peak-hour volume was increased 50%, the simulation results were similar to those discussed before. Although the network performance was inferior, due to the higher congestion, the flashing operation at the selected signalized intersections improved the traffic flow as compared to regular operation. Table 4 shows these results. The percentage improvement in the arterial performance when some signals were changed to the flashing operation mode was higher with the increase in volume. The D/V at the south entrance to Fashion Square (node 41) increased from 22.3 sec./veh. to 45.3 sec./veh., much above the maximum tolerable limit recommended by KLD & Associates.[3]

Fifty Percent Decrease in Afternoon Peak Volume

When the afternoon peak-hour volume was reduced 50%, the network performance was improved, too. At this volume, the overall performance was much better than in previous situations due to the lower traffic volume. Also, the D/V for side streets was reduced in all the intersections changed to flashing operation. The TID was reduced from 3.0 veh.-hr. to 0.64 veh.-hr. at node 5; from 5.16 veh.-hr. to 1.24 veh.-hr. at node 41; and from 3.96 veh.-hr. to 1.32 veh.-hr. at node 44. These reduced delays are lower than the ones included in the criteria for the installation of traffic signals mentioned earlier. A signal installed based on such criteria (see Table 1) is recommended to operate in the flashing mode during the low volume period. At least two consecutive hours of light traffic must occur to merit changing the mode of operation without confusion to drivers.

Table 5 shows the computer output results for these volume levels. The reduction in the total delay and in the S/V improved the average speed of the network. These reductions in delay also increased the fuel efficiency from 12.01 mpg to 12.51 mpg. The HC, CO, and NOX vehicular emissions decreased 6.1%, 7.5%, and 4.2%, respectively.

Morning Peak Volumes on Minor Streets at Nodes 5, 41, and 44

The final system simulation used the morning peak volumes for the side streets at the intersections whose signals were placed in the flashing mode. The major approaches and other minor streets were assigned the afternoon peak volumes as before. Table 6 shows the computer results for the simulation. As in the three cases discussed before, the TID at the intersections changed to flashing operation was reduced. The D/V was also reduced at almost all the links for these intersections. Only the south entrance to Fashion Square had an increase in the D/V, possibly because of the gap required for this traffic to enter the intersection.

The results in Table 6 show that the average speed and the delay per vehicle mile did not change. The total delay and D/V slightly increased. Vehicle stops were reduced by 3.2%. The drop in vehicle stops improved the fuel efficiency and reduced the vehicular emissions.

Flashing Intersection Impacts

To develop guidelines for the implementation of flashing traffic signals at selected intersections along arterial street systems, the aforementioned system simulation results were used to determine the effects of flashing signals on the approaches to the intersections. Tables 7, 8 and 9 contain measures of total delay and volume for each approach with a flashing signal indicated on the link node diagram for a 5-minute period.

These figures show that for the normal volumes (multiply figures in parentheses by 12 to obtain an hourly flow rate), the flashing operation reduced delay to traffic on the major street and increased the flow rate. In only one case (link 42-41) did the delay to minor street traffic increase significantly. When the volumes on all approaches were increased 50%, the resulting delay at that intersection was 45 sec/veh., which was equivalent to 4 vehicle hours/hr. This would be intolerable according to the Box study.[4]

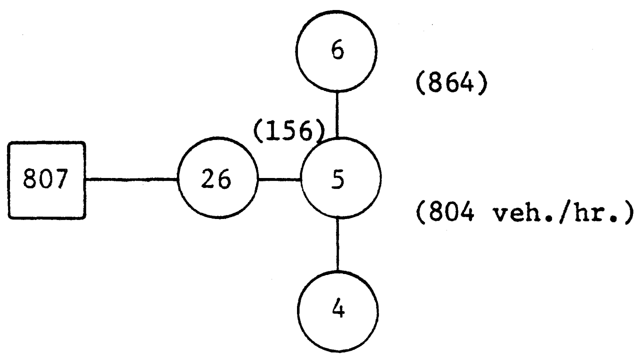
Table 7

Intersection at Wise Street

	Volume Level/Mode							
	Norm		+50%		-50%		AM	
Link	Reg.	Flash.	Reg.	Flash.	Reg.	Flash.	Reg.	Flash.
26-5 Minor	9.9* (13)**	3.3 (13)	15.7 (23)	14.9 (17)	5.4 (6)	0.9 (7)	4.4 (5)	1.8 (5)
4-5 Major	11.2 (67)	3.9 (70)	22.7 (91)	5.4 (108)	7.5 (41)	1.0 (32)	10.9 (72)	3.6 (74)
6-5 Major	5.7 (72)	4.2 (83)	11.7 (74)	3.9 (86)	2.2 (47)	1.3 (49)	4.8 (72)	4.1 (77)

*Total vehicle delay (minutes)

**Volume (5 minutes)



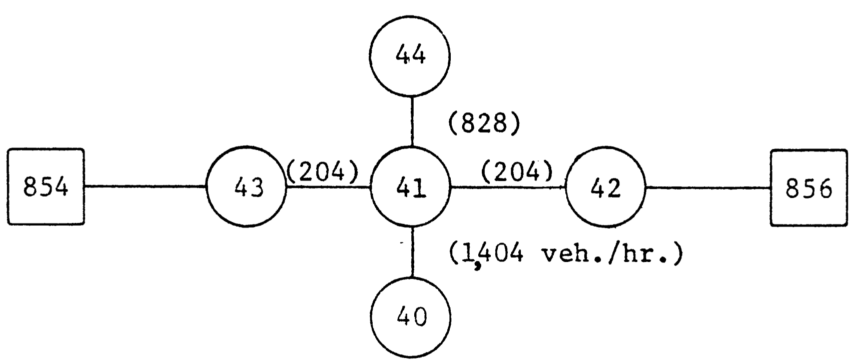
Intersection layout and normal approach hourly volume levels.
Ref. Figure 1.

Table 8

Intersection at Shopper's World and Fashion Square

	Volume Level/Mode							
	Norm		+50%		-50%		AM	
Link	Reg.	Flash.	Reg.	Flash.	Reg.	Flash.	Reg.	Flash.
40-41 Major	27.6* (117)**	8.6 (123)	31.9 (157)	22.1 (124)	10.3 (68)	2.6 (57)	20.1 (127)	7.1 (121)
42-41 Minor	7.6 (17)	10.3 (18)	8.5 (23)	19.6 (26)	2.2 (8)	0.9 (9)	1.3 (2)	0.8 (1)
43-41 Minor	2.3 (17)	2.4 (18)	3.9 (25)	10.4 (22)	2.3 (9)	1.2 (9)	6.3 (7)	0.8 (6)
44-41 Major	29.3 (69)	3.3 (72)	109.8 (94)	5.9 (100)	11.0 (32)	1.5 (31)	15.5 (44)	0.7 (51)

*Total vehicle delay (minutes)
**Volume (5 minutes)



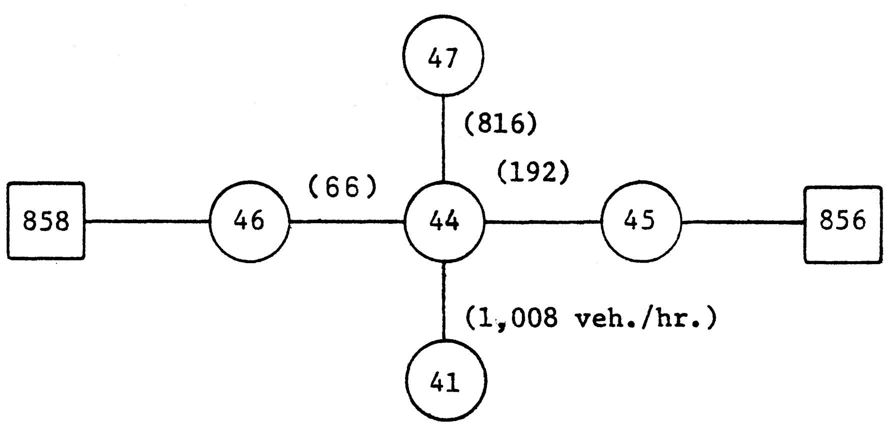
Intersection layout and normal approach hourly volume levels.
Ref. Figure 1.

Table 9

Intersection at Fashion Square and
Bill Edward's Oldsmobile

	Volume Level/Mode							
	Norm		+50%		-50%		AM	
Link	Reg.	Flash.	Reg.	Flash.	Reg.	Flash.	Reg.	Flash.
41-44 Major	19.7* (84)**	2.9 (92)	37.6 (108)	2.4 (86)	12.0 (49)	0.8 (39)	16.7 (92)	1.6 (83)
45-44 Minor	3.0 (16)	2.4 (14)	3.6 (21)	3.4 (22)	2.1 (7)	0.7 (7)	0 (0)	0 (0)
46-44 Minor	0.4 (5)	0.5 (5)	1.5 (7)	1.1 (7)	0.4 (3)	0.3 (3)	0 (0)	0 (0)
47-44 Major	16.7 (68)	9.5 (68)	38.2 (104)	38.4 (110)	5.1 (34)	4.8 (37)	14.9 (68)	9.9 (68)

*Total intersection delay (minutes)
**Volume (5 minutes)



Intersection layout and normal approach hourly volume levels.
Ref. Figure 1.

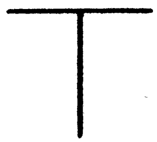
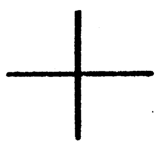
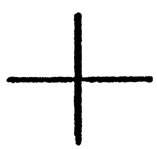
These observations directly relate to the interruption of continuous traffic warrant for traffic signal installations given in the MUTCD.[2] That warrant is designed to apply to "operating conditions where the traffic volume on a major street is so heavy that traffic on a minor intersecting street suffers excessive delay or hazard in entering or crossing a major street."[2] For the cases considered here (two-lane major street, one- or two-lane minor street), the minimum vehicular volumes as specified by the warrant for each of any 8 hours of an average day are 900 vph (total of both approaches) for the major street and 75 or 100 vph for the minor street. The simulation results indicate that this warrant may be too conservative for general conditions and that higher volumes can be handled with less delay with flashing signals.

For example, Table 10 provides summary statistics on the effects of flashing signal operation for different volume levels at the intersections shown in Tables 7, 8, and 9. Table 10 shows that at the T intersection, the flashing signal reduced delay for all volume levels shown (1-4). Even with a major street volume of 2,000 vph (#2), the simulation indicates that the flashing signal did not increase minor street delay; it was, in fact, slightly decreased. It is concluded, therefore, that for T intersections with major street volumes below 2,000 vph and minor intersection volumes at less than 300 vph, a flashing signal will reduce the TID.

The data on the two four-leg intersections do not provide as clear insight into the problem as for the T intersection. Firstly, a comparison of data points 5, 6, 9, and 10 indicates that where the directional distribution on the major street was rather balanced (9,10), volumes between 1,500 and 2,500 on the major street and 200 to 300 vph on the minor street provided acceptable conditions for flashing signal operations. On the other hand, for directional distributions approaching 3:2 (5 and 6) the flashing signal reduced total delay relative to the major street, but increased the delay to the minor street considerably. Flashing signals are, therefore, not recommended for consideration under such conditions.

TABLE 10

Summary Statistics on Flashing Signal Impacts

Type of Intersection	Vehicles Per Hour on Major Street (Total of both approaches)	Vehicles Per Hour on Major Street (largest approach volume)	Vehicles Per Hour on Higher Volume Minor Street Approach	Total Approach Delay min./hr. N	Total Approach Delay min./hr. F	Largest Delay Major Approach min./hr. N	Largest Delay Major Approach min./hr. F	Largest Delay Minor Approach min./hr. N	Largest Delay Minor Approach min./hr. F	Total Major Street Volume Highest Minor Approach Volume
	1. 1168	864	156	322	137	134	50	119	40	11
	2. 1980	1092	276	601	290	272	65	188	179	7
	3. 1056	564	72	181	38	90	16	65	11	16
	4. 1728	864	60	241	114	131	49	53	22	30
	5. 2232	1404	204	802	295	352	103	91	124	11
	6. 3012	1884	102	1849	696	1318	265	102	235	30
	7. 1200	816	28	310	74	132	31	28	14	50
	8. 2052	1524	84	518	113	241	85	76	10	26
	9. 1824	1008	192	478	184	236	114	36	29	11
	10. 2544	1296	252	971	543	451	458	43	41	11
	11. 996	588	84	235	79	144	58	25	18	13
	12. 1920	1104	--	379	138	200	119	--	--	--

CONCLUSIONS AND RECOMMENDATIONS

This study has shown that the recently suggested criteria for operating traffic signals in the flashing mode may be too conservative and that there are more opportunities for turning off signals than previously had been realized. It was found that major approach flows improve under all circumstances with a flashing signal in their advantage. For side streets, flashing signals were shown to create higher delays for very high traffic volumes as noted in Table 10.

Because each intersection is in many ways unique, the delay to side street vehicles should be carefully estimated prior to implementation of a flashing signal when main street volumes are at a peak. The NETSIM model has been demonstrated to be a valid tool for this task. Also, by its comprehensive nature, the NETSIM analysis reflects the effects of nearby streets and signals on flashing intersections that otherwise would not be reflected in the analysis of the single intersection.

The simulation tests conducted in the course of this study demonstrated that the NETSIM model replicated actual conditions fairly well. Problems that were encountered in applying the model can probably be corrected. In this regard, a revised NETSIM manual that includes better descriptions of the required inputs than are given in the current manual would help. The necessary components of the link-and-node diagram should be clarified. Major difficulties were encountered when encoding traffic-actuated signals. Since the logic required for this type of equipment is usually complicated, a more detailed description of its input parameters and procedures is needed, possibly with examples.

The capabilities of the model should be expanded to include pedestrian-actuated phases and coordinated control of dual-ring controllers. Urban grid networks usually have this type of equipment. The error messages should be revised to eliminate uncertainty in their interpretation.

Finally, the NETSIM model was selected for this research because of its ability to simulate stop sign performance; the traffic that faces a flashing red signal shall perform as if the signal were a stop sign. The computer results do not agree with the expected NETSIM performance. When the flashing alternative was tried, the stops per vehicle (S/V) at the individual side streets (links) that were facing a flashing red bulb should be equal to or greater than 1.0. Several of those links had an S/V less than 1.0, which is a clear indication of performance that should be corrected or at least called to the attention of users of the package.

The Department and cities should consider the use of flashing signals at intersections where the following volume conditions exist.

Type Intersection	Major Street Total Volume All Approaches, vph	Minor Street Highest Approach Volume, vph
T	2,000	300
Four-leg (balanced flow)	2,500	250
Four-leg (unbalanced flow, 3:2)	1,500	50

The above guidelines were inferred from the simulation results given in Table 10 and should be verified in the field. That is, intersections that exhibit the described volume conditions, particularly intersections of shopping centers and arterial highways, should be signalized in the flashing mode during peak conditions and volume and delay data taken. The NETSIM model should also be validated with the field data on flashing signals.

The time of operation of signals in the flashing mode was not directly addressed in this study. The primary motive for establishing a minimum time of operation derives from a desire to provide a consistency in a signal plan. That is, there is a fear that too many changes during the day in a signal's timing will confuse motorists. However, with the current emphasis toward making traffic operations more efficient, such a philosophy may be outdated. Accordingly, a minimum flashing period of two hours appears to fit both needs.

ACKNOWLEDGEMENTS

This study was financed with highway planning and research funds administered by the Federal Highway Administration.

The authors thank Jon DuFresne of the Culpeper district office and Jim Marshall of the city of Charlottesville for their time and assistance in providing the data. Special data were collected by John Shelor and Steve Blackwell of the Research Council. Barton C. Jennings assisted in running and evaluating the computer simulations.

12 A 0

REFERENCES

1. Benioff, Barry, Cynthia Carson, and Frederick C. Bock, A Study of Clearance Intervals, Flashing Operation, and Left-Turn Phasing of Traffic Signals, Volume 3. Flashing Operation, Federal Highway Administration, FHWA-RD-78-47, U. S. Department of Transportation, Washington, D. C., May 1980.

2. National Joint Committee on Uniform Traffic Control Devices, Manual on Uniform Traffic Control Devices for Streets and Highways, Washington, D. C., U. S. Federal Highway Administration, 1978.

3. Lieberman, E. B., G. F. King, and R. B. Goldblatt, "Traffic Signal Warrants," Final Report for the National Cooperative Highway Research Program, KLD Associates, Inc., December 1976.

4. Box, Paul C., and Associates, "Assembly, Analysis and Application of Data on Warrants for Traffic Control Signals," Report for the Signal Committee of the National Joint Committee on Uniform Traffic Control Devices, March 1967. Abridged version published in three parts in Traffic Engineering, Volume 38, No. 2 (November 1967), 32-41; Volume 30, No. 3 (December 1967), 22-29; and Volume 38, No. 4 (January 1968), 14-21, 56.

5. Smith, Wilbur, and Associates, "Traffic Signal Warrant for Heavy Traffic Volumes Occurring During Short Periods of Time (A Tentative Peak Hour Delay Warrant)," report for the West Virginia Department of Highways, April 1975.

6. The Application of Traffic Simulation Models, Special Report 194, Transportation Research Board, Washington, D. C., 1982.

7. Ross, Paul, and David Gibson, "Survey of Models for Simulating Traffic," Simulation Council's Proceedings Series, Volume 7, No. 1, An Overview of Simulation in Highway Transportation, Part 1, edited by James E. Bernard, Ph.D., June 1977.

8 Gibson, David R. P., "Available Models," Office of Development, Federal Highway Administration, May 1981.

9. Labrum, Willard D., and Ralph M. Farr, Traffic Network Analysis with NETSIM in a Small Urban Grid, Utah Department of Transportation, Division of Safety, Technology Sharing Report FHWA-IP-80-XX, Federal Highway Administration, June 1978.

10. Traffic Network Analysis with NETSIM, Implementation Package, A User Guide, FHWA-IP-80-3, Federal Highway Administration, U. S. Department of Transportation, Washington, D. C., January 1980.

APPENDIX A

GUIDELINES FOR FLASHING SIGNALS

This appendix describes various guidelines that have evolved over the years concerning the use of traffic signals in the flashing mode during select periods of the day. The practices are reviewed under the following classifications: The Manual of Uniform Traffic Control Devices (MUTCD), local warrants, and policy-oriented research studies. This material was the basis for deriving the summary given in Table 1.

The 1934 edition of the MUTCD included the following guidelines for the operation of traffic signals in the flashing mode.(1)

> All fixed-time traffic control signals, other than progressive systems of three or more intersections, should be changed from traffic control STOP and GO to flashing operation when for any period exceeding two hours traffic conditions fall below the volume requirements set forth ... except that if the accident warrant is satisfied the signal may be operated during such light traffic hours on a cycle of not more than 30 seconds.
>
> During certain hours the traffic at many signalized intersections is too small in volume to warrant STOP and GO operation. Signals at such locations may have great utility during hours when traffic flow is heavy. The change to flashing operation during light traffic periods not only facilitates the movement of traffic, but also tends to secure observance of the signals when they are operated as STOP and GO devices. In general STOP and GO operation is not warranted during the hours from 11:00 p.m. to 7:00 a.m. Special consideration should be given to warranted hours of operation on Sundays and holidays.

In the 1948 edition of the MUTCD these guidelines were included as follows.(2)

> When for a period of two or more consecutive hours the total vehicular volume entering an intersection having fixed-time signals installed under (the minimum vehicular volume) warrant falls below 50 percent of the minimum volumes stated above for urban and rural intersections, flashing operation shall be substituted for fixed-time operation for the duration of such periods of reduced volume.

> In many of the medium and smaller sized communities, a change to flashing operation will frequently be warranted by 8 or 9 p.m. on an ordinary evening. The impracticability of changing the method of operation many times during the day is recognized and therefore it is recommended that flashing operation be limited to not more than three periods in 24 hours.
>
> Since traffic-actuated signals, properly timed, cause a minimum of unnecessary delays, there is no justification for changing them to flashing operation during light traffic periods. Right-of-way is normally denied approaching motorists only when intersecting streets are in use by others or when safe approach speeds are exceeded.

The 1961 edition of the MUTCD stated that both low volumes and the respective time period should be considered.(3) It states for pretimed signals,

> When for a period of four or more consecutive hours any traffic volume drops to 50 percent or less of the stated volume warrants, it is desirable that flashing operation be substituted for conventional operation for the duration of such periods. However, such flashing operation should be restricted to no more than three separate periods during each day.

For traffic-actuated signals it states:

> Since traffic-actuated signals which are properly adjusted operate effectively in periods of light traffic and tend to cause a minimum of unnecessary delays, they should normally be operated at all times as stop-and-go devices. However, they may be placed on flashing operation because of certain special circumstances such as:
>
> 1. During breakdowns, repairs, or maintenance.
> 2. In conjunction with nearby pretimed signals on flashing operation.
> 3. Upon preemption by a railroad crossing protective signal.

The 1971 edition of the MUTCD makes only the following amendment regarding flashing operation (except in reference with safe operation or preemption by trains or emergency vehicles).[4]

> When a traffic control signal is put on flashing operation, normally a yellow indication should be used for the major street and red indication for the other approaches. Yellow indications shall not be used for all approaches.

The current (1978 edition) MUTCD has the same guidelines as the previous (1971) one.[5] Thus, the trend seen through the 1934, 1948, and 1961 editions of the MUTCD reveal a consensus toward flashing signals only if they will apply during relatively long periods (4 or more hours). No quantitative guidelines for the use of traffic signals during selected peak intervals in the flashing mode exist today.

Local Warrants

As implied in the last section, the criteria most widely used for the operation of traffic signals in the flashing mode is the lowering of intersection traffic volumes to a level less than that stated in the MUTCD minimum vehicular traffic volumes warrants. A study conducted by KLD Associates which included questionnaires to 157 cities, counties, and states, asking for (their) criteria for placing signals on flashing operation, produced the following results:[6]

> Of the 94 that answered the relevant question, 6 indicated that their jurisdiction had no specific criteria for flashing operations.. The remaining 88 responses were divided into four major groups:
>
> - 23 (26%) never converted signals to flashing operation (except for emergencies or malfunction).
> - 21 (24%) use the criteria of the 1961 edition of the MUTCD.
> - 25 (28%) other than the 50% mentioned above used a reduction in traffic volume as the criteria.

> The remaining 19 (22%) generally indicated the use of criteria not dependent upon traffic volumes. These included 9 respondents who flashed on a fixed, jurisdiction-wide time schedule and 3 who used comparative delay as the primary criterion.

Paul C. Box and Associates conducted a study for the Signal Committee of the National Joint Committee on Uniform Traffic Control Devices (NJCUTCD) which involved the collection of existing data in the area of signal warrant application.[7] They collected information up through 1967 on various subjects related to traffic signal warrants. Over 70 different studies on the delay subject were examined.

From the analysis of the collected field data and simulation studies performed by Box and Associates, a peak-hour warrant for traffic signals tied with flashing operation during sustained low-volume periods was recommended. The warrant was a delay of 3.0 vehicle hours of waiting time for two side-street approaches under two-way STOP sign control, or a delay of 2.0 vehicle hours for a single approach intersection. Table 1 shows the peak hour delay warrant suggested for a different number of controlled approaches. The type of signal control is indicated for the various ranges of the peak hour factor (PHF). To determine flashing needs, the peak-hour volume for the leg under consideration should be divided by the eight highest hours' volume. If the percentage obtained is 20 or greater, delay studies should also be conducted at other lower volume hours. Flashing operation should be considered during periods when the delay time for STOP sign control is less than 60% of the peak hour delay warrant for at least two consecutive hours.

Wilbur Smith and Associates developed a set of traffic signal warrants for very pronounced peak periods such as those which occur at large factories during the beginning and ending of shifts.[8] Among them is included one that sets volume criteria for placing signals in flashing operation. This is shown in Table 2. The figures represent the minimum minor street volumes below which signal control is not recommended, since it will increase rather than decrease minor street delay. When hourly volumes fall below these stated values, existing traffic signals should revert to flashing operation.

Table 1

Suggested Peak Hour Delay Warrant

Number of Controlled Approaches[1]	Vehicle Hours Delay[2]	Min. Veh. Vol.[3]	Type of Allowable Control by Peak Hour Factor[4]		
			.3 or less	.31 to .50	over .50
1	2.0	100	FA	SA or FA	any
2	3.0	100	FA	SA or FA	any
3	4.0	300	FA	SA or FA	any
4	4.0	400	FA[5]	any	any

1. When a single approach, or one leg with over 60% of common phase entering traffic, has less than two moving lanes, the warrant test may not be applied without first adding a second lane by parking prohibition for at least 100 feet on approach and departure sides or by widening, provided such widening is not physically impractical due to restricted built-up right-of-way, or other major physical barriers such as bridge abutments.

2. Waiting time delay, measured by 15 second queue count, at 15 minute summary intervals during the peak traffic hour of a typical weekday, or five peak hours of a Saturday or Sunday.

3. The entering volume of (3) above, divided by four times the highest 15 minute volume of the one or two lowest volume approaches which would operate on the same signal phase.

4. FA = Full-actuated type control.
SA = Semi-actuated type control.
These limitations apply only where the location will not be progressively timed as part of a signal system on one of the routes.

Source: Reference 7.

Table 2

Side Street Volumes Below Which
Signals Should Revert to Flashing Operation

Type of Intersection	Number of Approach Lanes on Minor Street	Minor Street Volume at which STOP Sign and Signal Control Produce Equal Total Minor Street Delay (Vehs/hour)
3-way	1	100
4-way	1	150
3-way	2	300
4-way	2	400

Source: Reference 8.

Policy Studies

Activity concerning flashing signal uses has also taken place at the state and local levels. For example, a recent study for the state of Colorado evaluated 57 potential alternatives for reducing fuel consumption.(9) In terms of the four criteria that were used, the strategy of setting signals in the flashing mode was ranked as follows:

- Cost Savings : Number 24 from top (with an estimation of 22¢ in other cost saved for each gallon of fuel saved). (7-79 prices)
- Impacts of Action : Number 5 from the top, in the most desirable category, "Highly Complementary with Other Transportation Objectives".
- Implementation Feasibility: Number 4 from the top. In the category, "Highly Feasible", requiring no legislation or bureaucracy and "In use elsewhere, generally popular."

. Summary of Profiles : Of the three categories of Popular but Weak; Efficient; Strong but Unpopular:

the "use of Flashing Yellow" appeared in the upper quartile of the Efficient category.

In another study, before and after studies were conducted on data from a large number of intersections around the country.(10) The largest data base was a computer tape containing the records of all traffic accidents in the city and county of San Francisco from January 1, 1974, to April 30, 1977. During that period, San Francisco was in the midst of a program to operate a large portion of its traffic signals in the flashing mode at nighttime.

The analysis of the data produced the following conclusions on how flashing operation affects delay and stops relative to the other forms of signal control:

Delay

- Flashing yellow/red produced less delay than any form of regular operation under all combinations of main and side street volumes.
- Flashing red/red produces less delay than pretimed control under all volume combinations, even where signals are coordinated on an arterial or in a network.
- Flashing red/red produces more delay than fully actuated and semi-actuated, isolated control at all volume ratios.
- Except at volume ratios (main street volume divided by side street volume) above 9, flashing red/red produces less delay than semi-actuated signals with a background cycle.

Stops

- Flashing yellow/red produces fewer stops than pretimed operation when the volume ratio is
    - above 1.1 for isolated signals
    - above 2.5 for signals timed along an arterial
    - above 3.0 for signals timed in a network

- Flashing yellow/red produces fewer stops than any of the types of actuated control under all combinations of main and side street volumes.
- Flashing red/red produces more stops than any form of regular operation under all combinations of main and side street volumes.

The study's recommendation for the operation of traffic signals in the flashing mode are as follows:

1. Flashing yellow/red operation may be used when two-way traffic volumes on the main street are below 200 vehicles per hour.

2. Flashing yellow/red operation may be used where the two-way main street volume is greater than 200 vehicles per hour provided the ratio of main street to side volume is greater than 3.

3. At locations that flash yellow/red, the accident pattern should be monitored. Signal operation should be changed to regular operation if the accident pattern during the flashing period meets or exceeds the following guidelines:

    - A short-term rate of 3 right-angle accidents in one year
    - A long-term rate of 2.0 right-angle accidents per million entering vehicles during flashing operation if the rate is based on 3 to 5 observed right-angle accidents.
    - A long-term rate of 1.6 right-angle accidents per million entering vehicles during flashing operation if the rate is based on 6 or more observed right-angle accidents.

4. Flashing red/red operation should not be used as an alternative to regular operation of a signal during early morning, low volume periods.

This study did not validate the following recommendations, but they were included.

5. It seems reasonable that flashing yellow/red operation not be used where side street drivers have a restricted view of approaching main street traffic.

6. In areas where stopped motorists are subject to assault, flashing yellow/red operation may be considered where it otherwise should not be.

7. The use of flashing red/red operation seems reasonable when it is needed for emergency signal operation, preemption by trains or emergency vehicles, or prior to turning on a signal at an intersection controlled by a four-way stop sign.

Subsequently, the city and county of San Francisco began a program to operate traffic signals in the flashing mode during low-volume periods. The program was intended to reduce energy consumption due to the vehicle delay, and to use less electrical power to operate signals. Upon total implementation of the program, it is estimated that drivers there would save 514,000 vehicle hours of delay, and 450,000 gallons (118,400 liters) of gasoline per year. It was found that a typical intersection (8 three-light 67 watt traffic signals and 8 "Walk-Don't Walk" 114 watt pedestrian signals), the electrical energy consumed dropped from 1.448 kilowatt hours to .268 kilowatt hour per hour of operation when changed to the flashing mode after being on regular operation. A 10% system-wide reduction in electrical energy consumption is expected when the program including 670 signals is fully implemented.(11)

The city of West Covina evaluated the energy conservation effect of setting traffic signals on all-red flashing operation "during early morning, low traffic volume hours."(10) All-red flashing operation was selected to have this mode available in case of an emergency. The results obtained show that total energy usage (vehicle fuel plus electrical) increased under the flashing all-red mode they used. This was due to the increased number of stops required on the major street. Their finding contrasted with San Francisco's flashing yellow/red results, which produced a reduction in the energy consumed.

The same study found that except for pretimed signals in a network, flashing yellow/red was the most efficient control in terms of fuel consumption.(10) A volume ratio of 3.0 or more was recommended for flashing operation based on their analysis of accident statistics.

APPENDIX A REFERENCES

1. U. S. Bureau of Public Roads, 1934, *Manual on Uniform Traffic Control Devices for Streets and Highways*.

2. U. S. Bureau of Public Roads, 1948, *Manual on Uniform Traffic Control Devices for Streets and Highways*.

3. U. S. Bureau of Public Roads, 1961, *Manual on Uniform Traffic Control Devices for Streets and Highways*, National Joint Committee on Uniform Traffic Control Devices (NJCUTCD).

4. U. S. Department of Transportation, Federal Highway Administration, *Manual on Uniform Traffic Control Devices for Streets and Highways*, NJCUTCD, 1971.

5. National Joint Committee on Uniform Traffic Control Devices, *Manual on Uniform Traffic Control Devices for Streets and Highways*, Washington, D. C., U. S. Federal Highway Administration, 1978.

6. Lieberman, E. B., G. F. King, and R. B. Goldblatt, "Traffic Signal Warrants," Final report for the National Cooperative Highway Research Program, KLD Associates, Inc., December 1976.

7. Box, Paul C. and Associates, "Assembly, Analysis, and Application of Data on Warrants for Traffic Control Signals," Report for the Signal Committee of the National Joint Committee on Uniform Traffic Control Devices, March 1967, Abridged version published in three parts in *Traffic Engineering*, Volume 38, No. 2 (November 1967), 32-41; Volume 30, No. 3 (December 1967), 22-29; and Volume 38, No. 4 (January 1968), 14-21, 56.

8. Smith, Wilbur and Associates, "Traffic Signal Warrant for Heavy Traffic Volumes Occurring During Short Periods of Time (A Tentative Peak Hour Delay Warrant)," report for the West Virginia Department of Highways, April 1975.

9. Voorhees, Alan M. and Associates, "Policy Alternatives to Reduce Transportation Energy Consumption," prepared for the Colorado Energy Research Institute, July 1979.

10. Benioff, Barry, Cynthia Carson, and Frederick C. Bock, *A Study of Clearance Intervals, Flashing Operation, and Left-Turn Phasing of Traffic Signals, Volume 3, Flashing Operation*, Federal Highway Administration, FHWA-RD-78-47, U. S. Department of Transportation, Washington, D. C., May 1980.

11. Quan, Harvey, "San Francisco's Experience with Flashing Signals," *Western ITE 29*, No. 1 (August-September 1975), 3-4.

APPENDIX B

TRAFFIC SIMULATION MODELS

This appendix reviews three of the most widely used traffic simulations distributed by the FHWA. The observations noted here were the basis for selecting the NETSIM model for use in this study.

TRANSYT

TRANSYT was developed by D. I. Robertson of the Road Research Laboratory in England. It is a signal optimization program. However, it contains, as an integral element, a simulation program that enables the user to either use or omit the optimization feature.[(1)]

The simulation program is used to calculate a performance index for the network for a given set of signal timings. The optimization feature consists of a "hill climbing" iterative optimization process which tends toward optimal signal phasing and offsets.

The program is totally macroscopic and completely deterministic; no random numbers are used. Uniform vehicle flow enters the upstream end of the furthest upstream link of the network. The flow arrives at the downstream end of the link, where it accumulates during the red phase. The departure rate leaving the link is assumed to be equal to the saturation flow when a queue exists at the signal approach, or equal to the arrival rate if no queue is present. The emergent platoon of vehicles now has a specific "shape", and arrives at the next downstream stop line with a delay appropriate to the length of the link and to the speed of progression on the link. Slight dispersion of the platoon is allowed depending on the length of the link and the amount of traffic. The shape of the platoons at any intersection reflects the effects of all the upstream intersections. The model provides for the vehicles' turning movements and for the arrival of vehicles at the stop line from such secondary flows as have turned onto the link.

Input requirements include input flows, actual speeds of progression on the links, and discharge capacities of the signals. The simulation program output consists primarily of delays and stops; however, it is able to represent the effects of changes in the signal system with great precision. A problem with the model is that STOP signs are handled by merely reducing the discharge according to the opposing traffic volume.

The TRANSYT program has been tested extensively, both in Europe and the United States, and has significantly demonstrated effective results. An American version of TRANSYT - 7F, has a preprocessor to provide a simplified input and a postprocessor to provide a time-space diagram and improved output.(2)

In a British Road Research Laboratory study it was found that TRANSYT accurately predicted network delay and was very effective in obtaining optimum offsets. The process was very stable since a standard deviation of about 1% was found among delay results for optimum signal settings obtained from different sets of initial settings.

SIGOP II

SIGOP II (Signal Optimization) is a descendant of TRANSYT and SIGOP I and like them is an optimization program. Like TRANSYT, it has a macroscopic model of traffic flow which can be used to evaluate the stops and delays of an existing signal system.(1)

SIGOP II can handle both arterial and urban street grid networks. This version gives particular attention to the treatment of turning movements, multi-phase signal control, and short-term fluctuation of volume about the mean. Parameters considered in the optimization process include vehicle delay, vehicle stops, and the relationship of queue length to available storage capacity.(3)

The optimization procedure used in SIGOP II minimizes system "disutility". The optimization procedure can handle policy decisions to provide excellent service along a specific street at the possible expense of some of the cross streets. This is done through input weighting of importance of the links representing the preferred street.

A disadvantage of SIGOP II is that unsignalized intersections must be treated with source/sink nodes or a dummy signal must be inserted. The traffic model in SIGOP II is not as accurate as the one in TRANSYT, but this is outweighed by the smaller computer time requirements. An advantage of SIGOP II is that it is able to accurately represent traffic behavior when congestion occurs.(3)

Input preparation is straightforward after mastering the notation for describing multiple-phase signals. Error messages and diagnostic tests are embedded in SIGOP II to help the user. Output includes time-space diagrams of the optimal signal setting along specified arterials as well as link-by-link statistics.

NETSIM

The NETSIM (NETwork SIMulation) model is based on a microscopic simulation of individual vehicle trajectories as they move through a street network.[4] It has the capacity to treat all major forms of traffic control encountered in the central areas of American cities. It includes a set of "default" values for many input parameters, therefore reducing the necessity to make traffic studies to obtain them.

The model treats the street network as a series of interconnected links and nodes along which vehicles are processed in a time-scan format, subject to the imposition of traffic control systems. It is designed primarily to serve as a vehicle for testing relatively complex network control strategies under conditions of heavy traffic flow. It is particularly appropriate for the analysis of dynamically-controlled traffic signal systems based upon real-time surveillance of network traffic movements. It may also be used to evaluate strategies for simple traffic engineering problems (e.g., parking and turn controls, channelization, and one-way street systems) and a full range of standard fixed-time and vehicle-actuated signals. In addition to the normal data on vehicle performance such as speed, delay, and vehicle-miles, the output data include estimates of fuel consumption and vehicular emissions.

NETSIM requires considerable preparation and codification prior to utilization. It has been approvingly subjected to an extensive program of field testing and validation. The entire model is written in FORTRAN IV and can be run on the IBM 360/370, CDC 6600, or upper series UNIVAC machines. It requires a local core memory of 256 kilobites and is highly efficient. The program's structure is modular, consisting of a preprocessor, simulator, fuel consumption and emissions, and a data postprocessor.

APPENDIX B REFERENCES

1. Ross, Paul, and David Gibson, "Survey of Models for Simulating Traffic," Simulation Council's Proceedings Series, Volume 7, An Overview of Simulation in Highway Transportation, Part 1, edited by James E. Barnard, Ph.D., June 1977.

2. Gibson, David R. P., "Available Models," Office of Development, Federal Highway Administration, May 1981.

3. Labrum, Willard D., and Ralph M. Farr, Traffic Network Analysis with NETSIM in a Small Urban Grid, Utah Department of Transportation, Division of Safety, Technology Sharing Report FHWA-IP-80-XX, Federal Highway Administration, June 1978.

4. Traffic Network Analysis with NETSIM, Implementation Package, A User's Guide, FHWA-IP-80-3, Federal Highway Administration, U. S. Department of Transportation, Washington, D. C., January 1980.

APPENDIX C

DATA CODIFICATION

The codification of the data gathered was difficult. The User's Guide for the NETSIM Model was not clear in many respects. The first requirement to operate the model is a coded link-and-node diagram of the network to be simulated. Nodes and links must be differentiated between internal, entry, exit, and source/ sink nodes. Internal links are inside the network, and statistics are accumulated that pertain to these links. Entry links serve to introduce vehicles at the input flow rate specified using the volume data obtained. Vehicles are emitted when signals and traffic conditions permit. No statistics are accumulated for these links.

Exit links receive all the vehicles discharged from the network. Their geometric characteristics are not required. Source (or sink) nodes are associated with internal links and are connected to them by pseudo-links. These nodes exit (or absorb) vehicles onto (from) that internal link, and are used to represent traffic at such facilities as garages, parking lots, side streets, or alleys not represented on the network diagram. For each simulation sub-interval, only the net flow of traffic (without vehicle type classification) is specified.

The first link-and-node diagram prepared did not accomplish its intended purpose. The simulation attempted using this diagram as the coding reference, failed to produce the information expected. The diagram required was more complex than the one utilized. In order to simulate intersections, it was required to include additional dummy nodes at all approaches, so as to obtain statistics of the performance of each link. It should be pointed out that this was not clearly explained in the user's guide manual. To simulate the traffic performance at an intersection, it was found that it required a link-and-node diagram as shown in Figure C-1.

To codify the link's operation (card number 5), the free flow speed, queue discharge rate, and lost time or queue start-up delay was needed. The free flow speed used was the posted speed limit and the discharge rate was assumed to be 2.2 seconds. The start-up delay used was the default value provided by the model. The other information was obtained from field inspections.

The model uses turning movement (card number 7) as a percentage of traffic from each approach or as actual counts. For those links where actual counts needed no adjustment, they were used as such. When adjustments were necessary, percentages were codified.

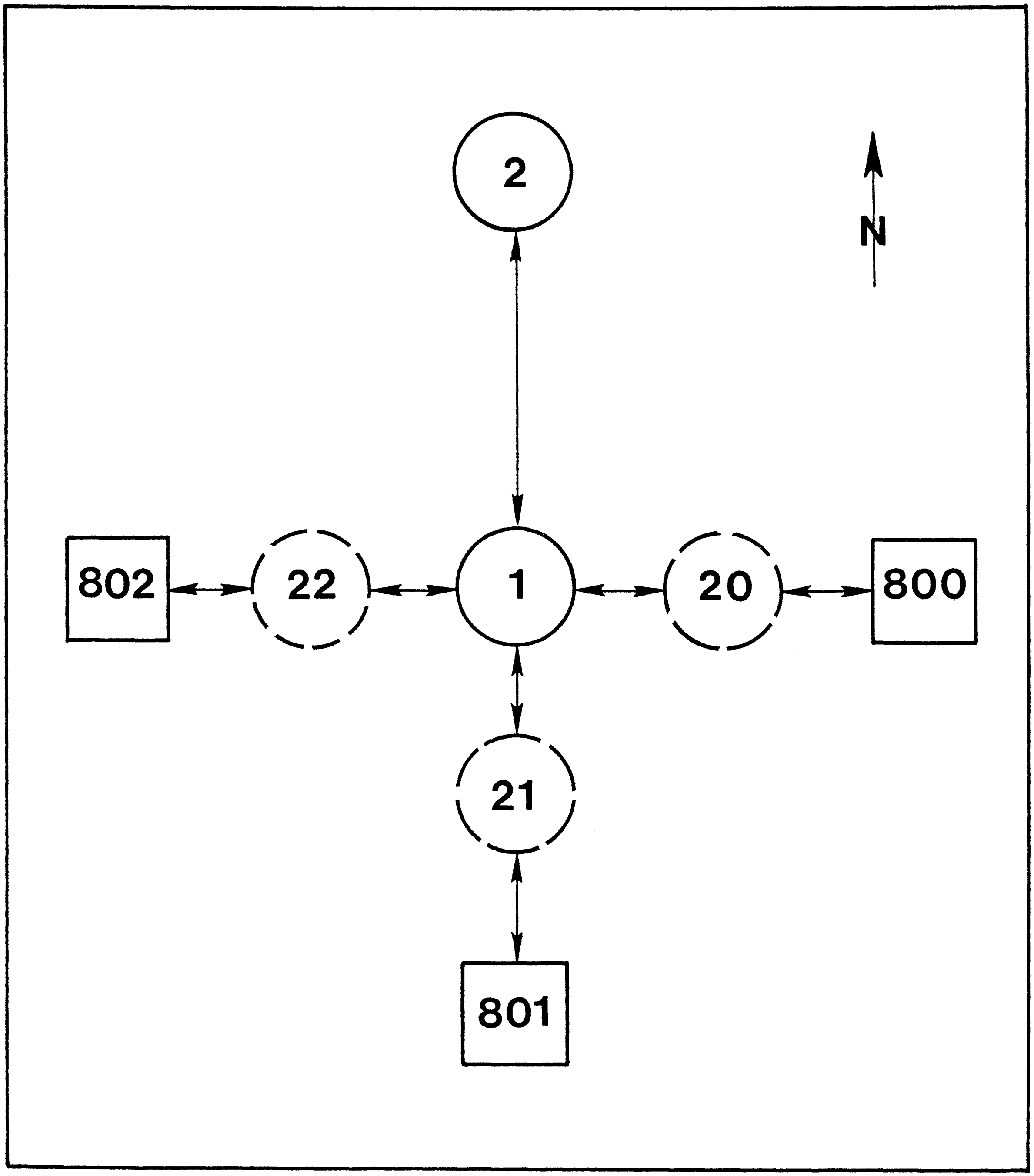


Figure C-1. Link-and-node diagram for the intersection of Route 29 north and Ivy Road and University Avenue — nodes 20, 21, and 22 are "dummy" nodes.

Where it was not clear from the network geometry which left-turn movements could be done without conflict, an auxiliary topology card (card number 8) was included to make the model recognize the existing conditions and eliminate the traffic impedance associated with left-turning vehicles.

Entering the timing, phasing, and detector locations was, indeed, the most difficult part of the codification. Although it is not indicated in the user's manual, the NETSIM model does not include desirable features such as pedestrian-actuated phases and coordinated control of dual-ring controllers.

All traffic signals in the case study arterial are traffic actuated and most are dual-ring controllers. At the intersection of Wise Street and Route 29 north (see Figure C-1), a pedestrian phase is provided. The section from Massie Road to Barracks Road is interconnected, with the Barracks Road controller acting as the master for system coordination. This controller is also of the dual-ring type.

From observations at the intersection of University Avenue, Ivy Road and Route 29 north, it was found that only four phases were in operation, instead of five as indicated on the city traffic engineer's phasing and timing sheet. Timing of these four phases was coded as obtained from the city traffic engineer. The fifth phase was ignored. The operation of the signals at the intersections of Massie Road, Arlington Boulevard, and Hydraulic Road with Route 29 north was coded as obtained from the municipality's data. The pedestrian-actuated phase at the intersection with Wise Street could not be included per intrinsic NETSIM limitations.

As mentioned, the controller at the intersection with Barracks Road is in dual-ring operation and it was codified as such. Simulations made with this coding were not successful. The controller phasing remained in the first phase and a queue was developed at the intersection's approaches that was never discharged.

As generally known, traffic-actuated controllers require detectors to calculate the lapse of time assigned to each approach. A NETSIM phase operation card (card number 17) has to be included for each phase to indicate the location of each detector (approach and lane). Detectors that call for a particular phase, as well as those that modify the phase's duration, have to be identified by their location. Right-turn pockets must be coded as a 4 or 5; a 4 is used if there is a left-turn pocket also, and 5 if not. Left-turn pockets are always coded as 5. This is not indicated with the specifications for the phase operation cards, but is a requirement for the NETSIM surveillance cards (card number 25).

Surveillance cards were said to be optional in the user's manual, but when simulation was attempted without providing one of these cards for each access controlled by a traffic actuated controller, the simulation was aborted. Subsequent attempts at eliminating the surveillance cards gave more error messages, a clue that they were required for all traffic actuated controlled access.

All the findings while coding and running the program using the preprocessor to identify the coded errors led to a successful run, and finally an acceptable output. To obtain this, the link-and-node diagram had to be redrafted. Then, all cards were re-coded using the new diagram. The interconnection master controller at the intersection of Barracks Road and Route 29 north was assumed operating in single-ring mode; therefore, the timing and phasing for this controller was modified. Only four signal phases were included instead of the five actually in operation. The pedestrian-actuated phase at Wise Street was not included. The detector lane location was corrected in the phase operation cards. A NETSIM surveillance card was provided for each approach controlled by a traffic actuated controller to identify each detector in the link. A fixed-time control signal card (card number 10) was added for each unsignalized intersection.