

OPERATIONAL STUDY OF SIGNALIZED
DIAMOND INTERCHANGES

by

Charles Pinnell and Donald G. Capelle

Reprinted from Bulletin 324 (1962)
Highway Research Board, Washington, D. C.

Operational Study of Signalized Diamond Interchanges

CHARLES PINNELL and DONALD G. CAPELLE, Texas Transportation Institute, Texas A & M College

This paper was developed from a research project on diamond interchanges conducted by the Texas Transportation Institute in cooperation with the Texas Highway Department. The project had the general objective of developing criteria useful in the capacity evaluation, design, and signalization of diamond interchanges. An earlier report, presented at the 40th Annual Meeting, included a procedure for evaluating the capacity of signalized diamond interchanges. This paper presents data from operational studies designed to develop criteria for the design and signalization of diamond interchanges.

Four separate field studies were conducted at a signalized diamond interchange on Interstate 35W in Fort Worth, Tex. By modifications to the control equipment at this interchange, three separate signal phasing arrangements were evaluated. Also, operations with both fixed-time and traffic-actuated control equipment were studied. Recommendations are made regarding both the signal phasing and the equipment for use at signalized diamond interchanges.

The operational studies also permitted the evaluation of interchange design elements that affected traffic operations at the facility. Various aspects of design that affect operation are discussed and illustrated by a recommended design.

Finally, examples illustrating the capacity-analysis, design, and signalization of diamond interchanges are presented. These examples demonstrate the application of the research findings to specific design and operation problems.

• THIS REPORT presents results from research studies on diamond interchanges conducted by the Texas Transportation Institute in cooperation with the Texas Highway Department. These studies were conducted in connection with Research Project RP-16, "Ramps and Interchanges," and had the objective of investigating the capacity, design, and operation of conventional-type diamond interchanges.

The initial studies were designed to evaluate only the capacity of a conventional-type diamond interchange. The procedure and results of these studies were reported in a paper by the authors (1) which was distributed to the various districts and offices of the Texas Highway Department.

In addition to the capacity studies, there existed a need for additional research to develop data that would serve as criteria in the design and signalization of diamond interchanges. The results of this research are presented as a major portion of this report.

INTERCHANGE TYPE

There are many design variations of the diamond interchange, and numerous conditions may exist affecting its operation. The research studies conducted in connection with this project involved only the conventional-type diamond interchange, as shown in

Figures 1 and 2. The sites selected for study were free of any special conditions such as signalized intersections in the near vicinity of the interchange. The data and recommendations presented are directly applicable only to the type interchange illustrated and similar diamond interchanges without frontage roads. However, they should serve as a guide to engineering judgment in treating special designs and conditions.



Figure 1.

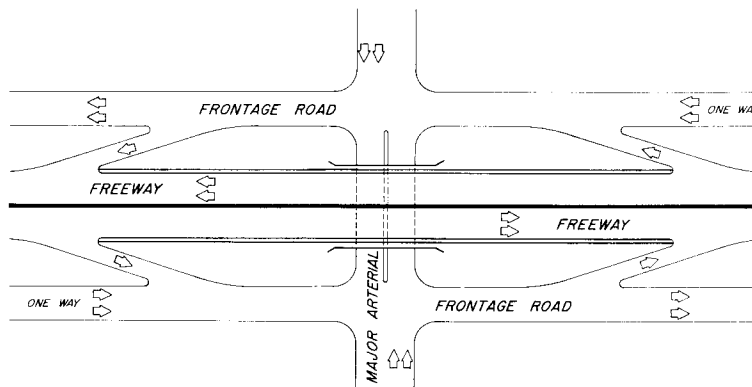


Figure 2. Diamond interchange, conventional arrangement.

SIGNAL OPERATIONS

Requirements

A complex signal system is required to control traffic at a diamond interchange due to the proximity of the two signalized intersections and the variations of traffic maneuvers encountered in interchanging traffic. The signalization should perform the following two basic functions:

1. Separate all high-volume conflicting movements in the interchange area.
2. Minimize storing of vehicles between the two intersections.

In considering the signal system to be used at a diamond interchange, it is natural to assume that the type of signalization would depend on the traffic volumes and movements experienced. Because many of the future diamond interchanges will be a part of new freeways extending into relatively undeveloped areas, it is conceivable that numerous volume conditions will be experienced during the design life of an interchange. Thus, it appears that numerous phasing arrangements would be necessary to accommodate the various traffic conditions that are likely to be encountered. However, this is not entirely true due to the peculiarities of diamond interchange operation.

Inasmuch as the two signalized intersections of a conventional-type diamond interchange are usually spaced approximately 220 to 290 ft apart (center to center), two factors that influence the signal phasing are (a) amount of vehicle storage between the two intersections and (b) volume of left turns from interior approaches. Extreme care must be exercised to assure that the storage limit of the interior approach is not exceeded. In addition, high-volume left turn movements can quickly exceed the storage capacity on interior approaches because only one lane is generally available for the storage of left turning vehicles.

Signal Phasing

Figure 3 shows two possible phasing arrangements for diamond interchange signalization. Although these phasing arrangements represent only two of numerous possible sequences, they illustrate the problems incurred in developing signal phasings for diamond interchanges.

In Sequence I (Fig. 3) clearance phases must be added following phases A and B to clear the interior approaches for storage of the frontage road movement on phase C. This in effect creates a four-phase cycle (if the two clearance intervals are considered approximately equal to one phase) with a considerable waste of time. A second disadvantage of Sequence I is the sluggish operation frequently encountered on the phase A movement. This results from numerous cars being stored on the interior approaches during phase C. When the phase A movement is initiated, the traffic on the major street

approach is delayed until the interior approach traffic can move out. Thus, in effect, a double starting delay is imposed.

The third and most serious disadvantage of Sequence I is the capacity limitations placed on the frontage road movements. The amount of traffic that can be moved from a frontage road approach during phase C is governed by the storage capacity of the interior approaches. Therefore, this sequence is inadequate to accommodate large frontage road movements.

Sequence II allows the interior approaches to clear on phase B and gives preference to moving major street traffic. However, a serious left-turn storage problem is often created by this sequence. Left turns from both of the major street approaches are stored during phase A, and it must be considered that an average diamond interchange can store only a maximum of 7 left-turning vehicles per lane on an interior approach. When a heavy left-turn movement from a major street approach occurs (which frequently happens), the storage capacity for left-turning vehicles is exceeded and blocking of the intersections results. Sluggish operation will follow phase C, and storage capacity limitations will exist on the ramp and/or frontage road movements as in Sequence I.

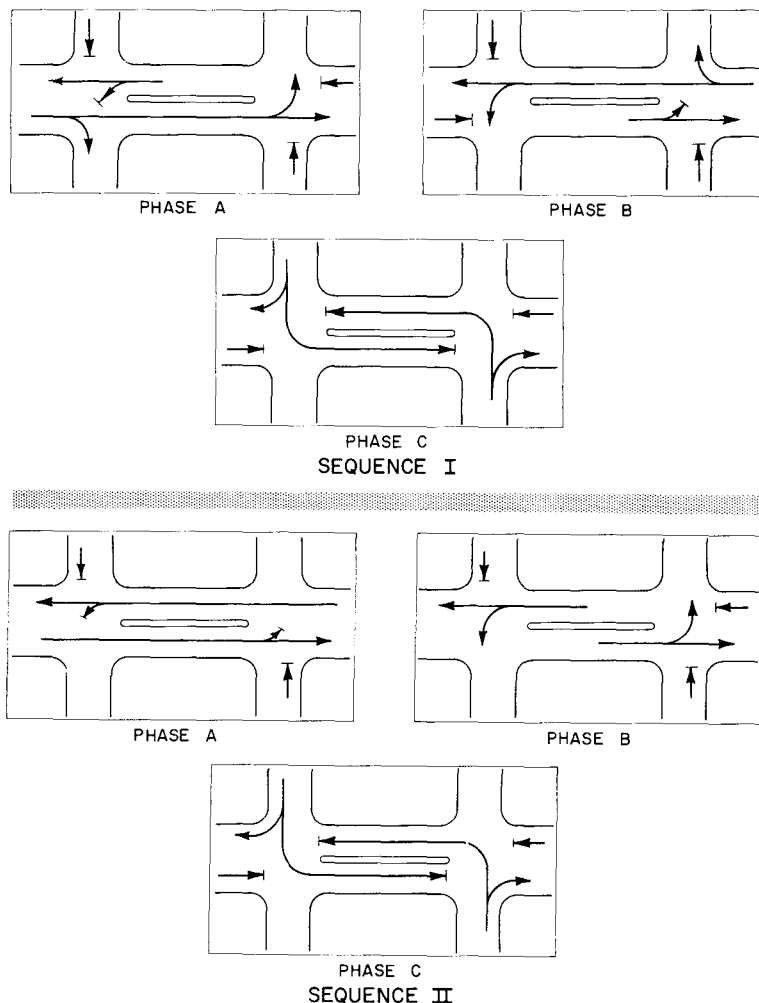


Figure 3. Signal phasings.

Recommended Phasing

Other three-phase arrangements such as Sequences I and II yield the same basic problems of inadequate storage and sluggish, inefficient operation. Consideration of these facts and the requirements of diamond interchange signalization led to the conclusion that the four-phase sequence shown in Figure 4 would serve best for all traffic conditions. This sequence has been utilized at diamond interchanges by the city of Houston, the California Highway Department, and perhaps other agencies, but the advantages and efficiency of this phasing have not been fully realized.

The two most serious problems encountered with a three-phase system (as previously discussed) are its inability to accommodate large frontage road movements and left turns from interior approaches. These problems are eliminated with the recommended four-phase system (Fig. 4).

Each of the four approach movements is given a separate phase and is permitted to move through the entire system upon receiving a green indication. This eliminates the storage capacity limitations that develop on the interior approaches with other phasing arrangements. Consideration of each movement in the four-phase sequence will show that storing of vehicles on the interior approaches is practically eliminated.

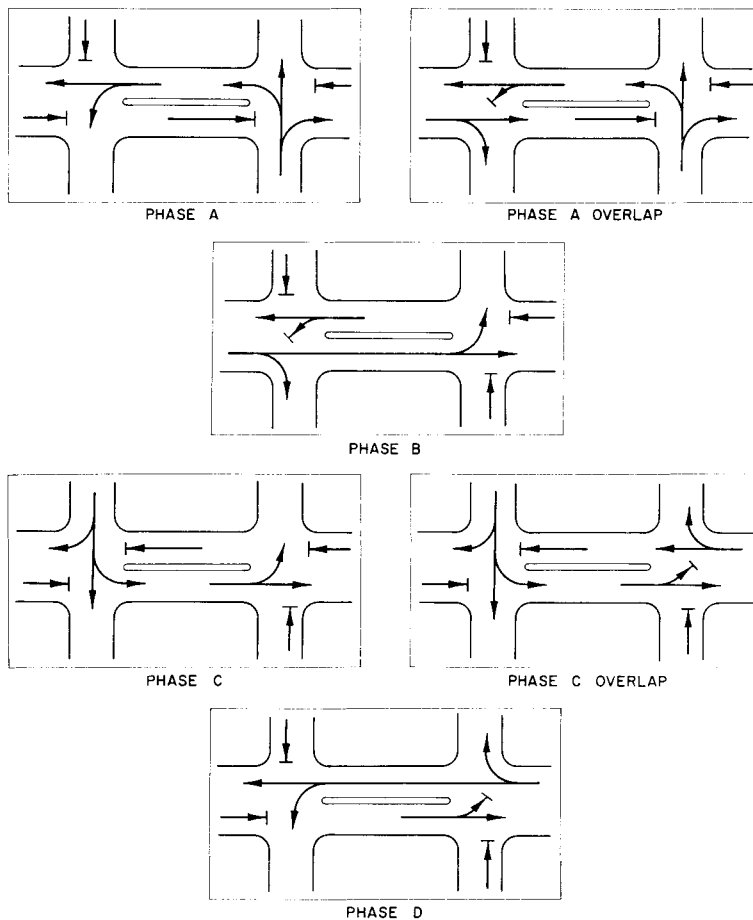


Figure 4. Recommended signal phasing for conventional-type diamond interchange.

The only vehicles requiring storage are those making a U-turn movement from a frontage road during the last 6 to 8 sec of a frontage road phase. This seldom stores more than 2 vehicles per cycle and has very little detrimental effect on operation. Thus, the left turn storage problem is eliminated with this phasing.

An additional advantage of the recommended phasing is the efficiency that can be obtained. An overlap of the frontage road and major street phases (phases A and C overlap) is possible due to the starting delay and travel time incurred by the major street traffic in moving from one intersection to the other. This overlap utilizes the green time per cycle better and permits the movement of large volumes through the interchange with average cycle lengths in the range of 60 to 80 sec.

Therefore, it was concluded that the recommended four-phase sequence is the best signal phasing for a conventional-type diamond interchange.

SELECTION OF CONTROL EQUIPMENT

A significant problem encountered with diamond interchange operation is the selection of the type of signal equipment (fixed time or vehicle actuated) that will yield the best results in controlling the interchanging traffic. One of the objectives of this project was to study this problem.

There are four significant factors that influence the selection of equipment:

1. Volume fluctuations;
2. Equipment flexibility;
3. Coordination; and
4. Economics.

Volume Fluctuations

Volume fluctuations during off-peak and peak periods of operations are common knowledge to traffic engineers and should be given consideration in any well-designed signal system. Studies of vehicle arrivals by 5-min intervals at several diamond interchanges revealed significant volume variations within the peak hour. A plot of 5-min demand volumes on the four approaches of the Cullen interchange on the Gulf Freeway in Houston, Tex. is shown in Figure 5. This plot shows that each of the approaches had a different peaking pattern and a wide fluctuation of 5-min demand volumes.

A superimposition of these volume plots will show a comparison of the short periods of peak flow. Little overlapping of the peak periods is evidenced for the four approaches and thus a single timing plan for the peak hour would be inefficient.

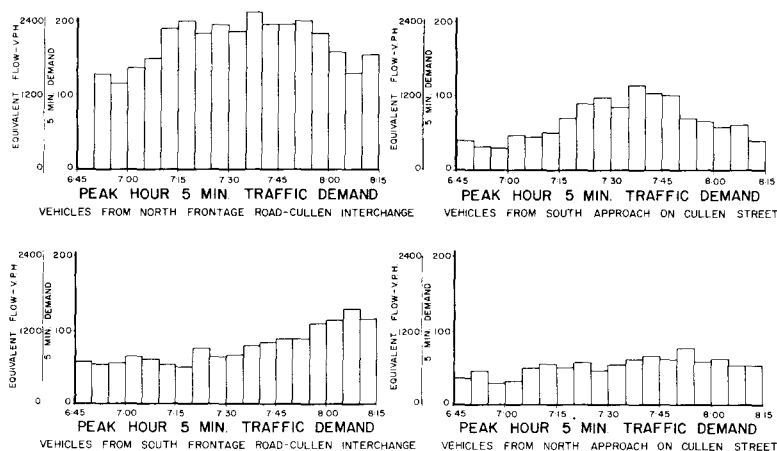


Figure 5. Demand volumes, Cullen Boulevard interchange, Houston, Tex.

This volume fluctuation emphasizes the need for equipment that can adjust cycle and phase lengths to traffic demand during both off-peak and peak periods of traffic flow, if maximum operational efficiency is to be obtained.

Equipment Flexibility

An important feature of signal flexibility is the ability to accommodate special conditions that may develop during peak periods of operation. Conditions such as stalled vehicles, minor accidents, or other disruptions of normal traffic flow can result in tremendous backlogs of traffic on the interchange approaches. These conditions commonly occur during peak periods and were observed frequently during the signalization studies. If the signal system does not have the flexibility to temporarily increase the cycle lengths to accommodate the accumulated demand, the interchange will be congested until the traffic demand diminishes.

Coordination

A third factor is that of progressive movement for the through traffic on the major street. Progression of this through traffic is desirable. However, because the signal system at the interchange must operate on a multiphase sequence, the interchange area represents a bad timing point in the coordinated system.

It must also be considered that the through traffic for which progression is desired represents a minor percentage of the total traffic entering the interchange area. Analysis of volume counts at the Berry Street interchange in Fort Worth and the Cullen and Wayside interchanges in Houston indicated that the volume of the through movements represented only approximately 25 percent of the total interchanging traffic. Therefore, efficient operation of the entire interchange system should receive more priority than that of providing progression for the through traffic on the major street.

The interchange can be designed so that traffic will not be delayed for more than one cycle, and some progression for the major street traffic can be obtained by timing away from the interchange as shown in Figure 6.

Economics

The relative cost of fixed-time and traffic-actuated equipment for complete signalization should also be considered. Specific equipment costs are not compared in this report because these will vary with time, type of equipment, and manufacturer. However, consideration of the requirements of one system over the other and the relative costs can be made.

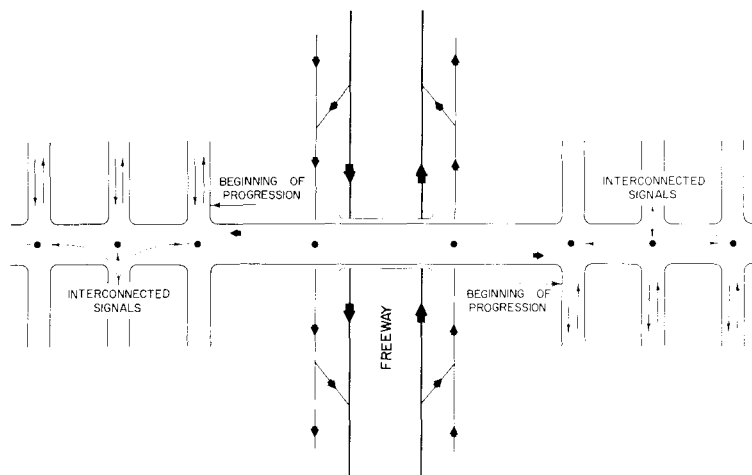


Figure 6. Progressive timing of signal systems adjacent to a diamond interchange.

Basic equipment, such as signal heads, mast arms, and much of the wiring, would be the same for both systems. The basic difference in cost for the two systems is related to the following factors:

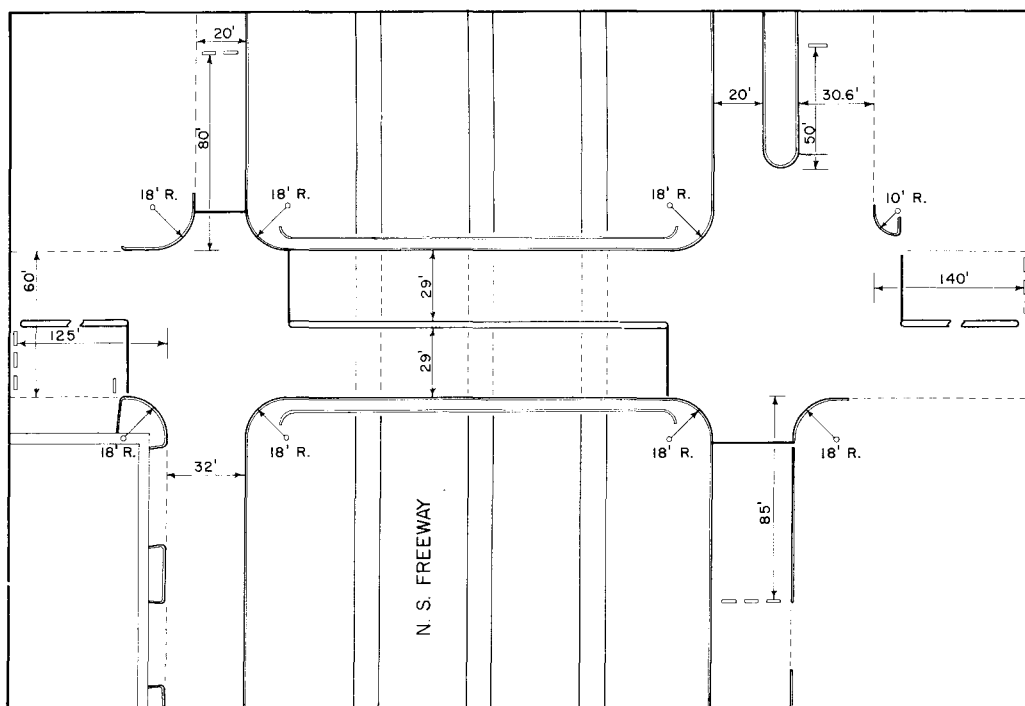
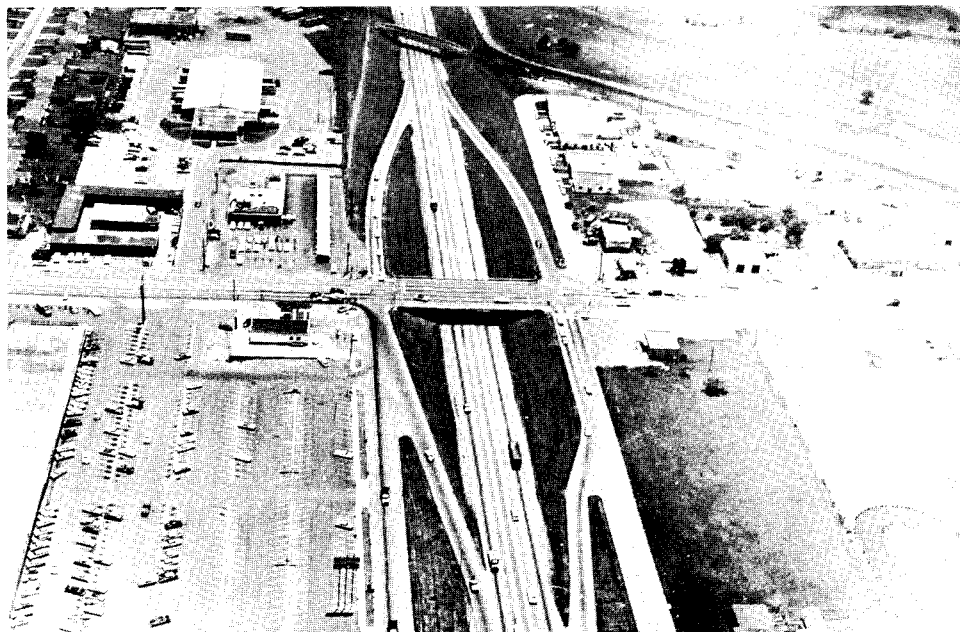


Figure 7. Berry Street interchange, Fort Worth, Tex.

1. Additional cost of actuated control units; and
2. Additional cost of the detectors (initial cost and installation) required for the actuated system.

The difference in cost for the two systems (fixed time vs traffic actuated) is a relatively small percentage of the total installation cost and loses significance when prorated over the design life of the facility.

OPERATIONAL STUDIES

The objective of the operational studies at an existing diamond interchange was to evaluate several signal phasing arrangements and to study the adaptability of actuated signal equipment to diamond interchange operation. Previous work had given an indication of the type of operation to be expected, but no field studies had been conducted to verify the operation anticipated.

Study Location

The Berry Street Interchange (Fig. 7) on IH 35W in Fort Worth, Tex., was selected as a study site for the operational studies. The geometrics of this interchange were

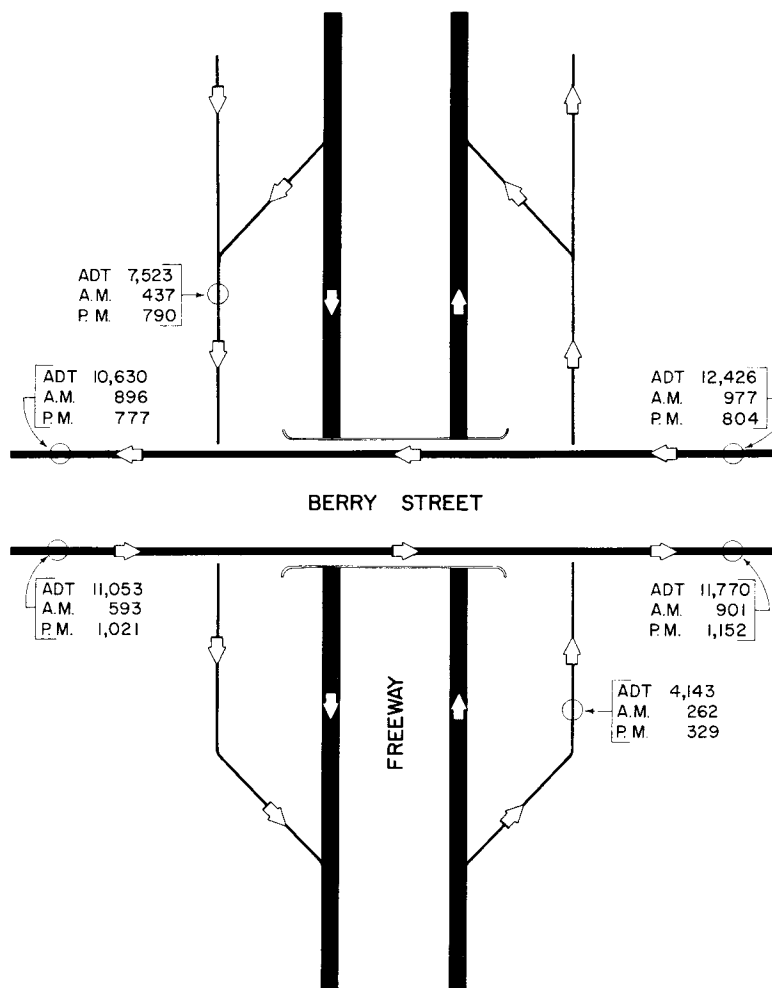


Figure 8. Traffic volumes, Berry Street interchange.

essentially those of a conventional-type diamond and are representative of numerous diamond interchanges that have been constructed. Traffic volumes (Fig. 8) at this interchange were of sufficient magnitude to provide adequate study conditions. The traffic control equipment at the interchange at the beginning of the studies consisted of a three-phase volume-density controller with dual-clearance timers.

The Traffic Engineering Department of Fort Worth agreed to modifications of the signal phasing and control equipment; consequently, the site provided an excellent study location for evaluating actuated control equipment under various phasing arrangements.

Study Procedure

Four separate studies of traffic operations were conducted at the Berry Street interchange. All of these studies were conducted during the late afternoon peak period of flow (4:00 to 5:30 p. m.) on either a Wednesday or Thursday. Data were recorded on the following:

1. Traffic volumes per cycle from each approach;
2. Cycle lengths; and
3. Phase lengths.

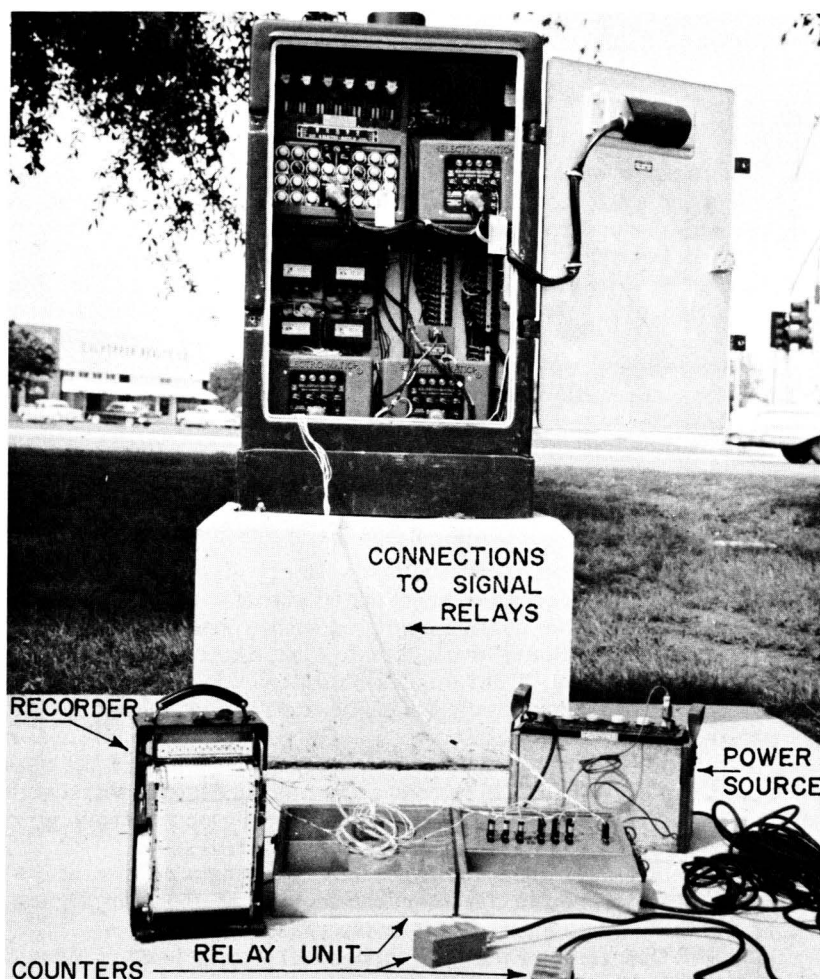


Figure 9. Recording equipment.

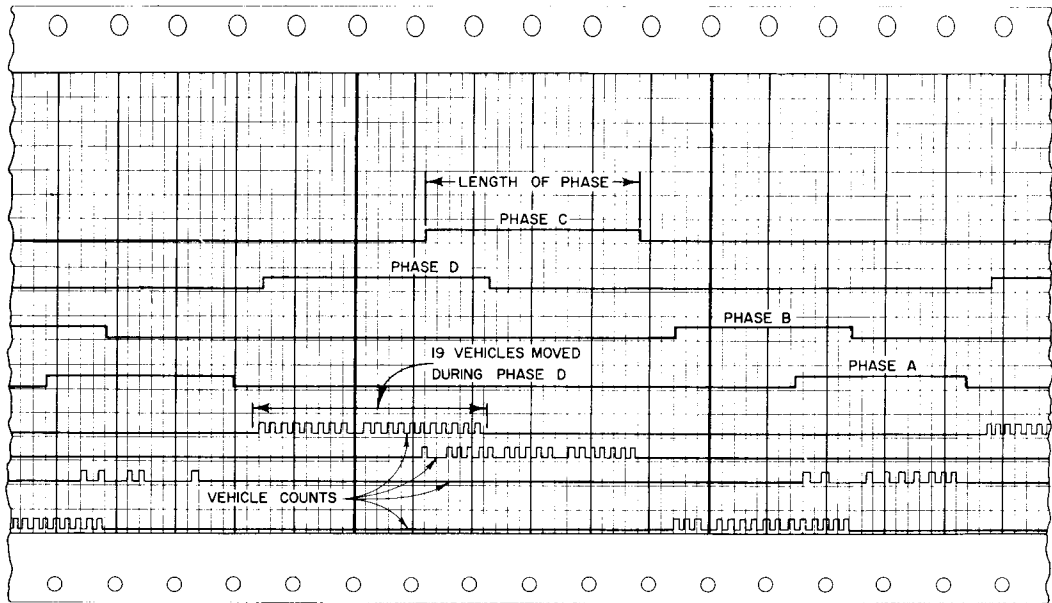


Figure 10. Sample data chart.

In addition, interchange operations were observed and notes were made on the general efficiency of the system. Queue lengths on the approaches, the ability of the signal system to clear the traffic demand on each cycle, and smoothness of operation were used as criteria for evaluating the efficiency of the operations.

The data were recorded by the multi-pen recorder and equipment shown in Figure 9. Volumes on each of the approaches were recorded by actuating switches connected to pens on the recorder. Vehicles were indicated by a "blip" on the recording tape. The phase lengths and cycle lengths were obtained by wiring the recorder to the relays controlling the various phases of the signal cycle. The energizing of a signal on a particular phase actuated a pen. Because the chart moved at a constant speed, the length of each phase and the total cycle length could be readily measured. A sample of the recording chart and the data recorded is shown in Figure 10.

Berry I: Three-Phase Operation

The first of a series of studies conducted at the Berry Street interchange consisted of an evaluation of the existing actuated three-phase signal system which had been in operation for several years. The system operated with a phasing arrangement as shown in Figure 11. Dual clearance timers were used to clear the interior approaches after phases A and B so that the phase C movement would have adequate storage. These clearance intervals contributed to a long cycle length because they required a total of 16 sec.

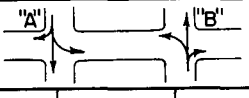
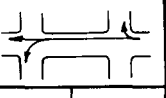
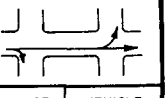
The amount of green time that could be efficiently allotted to the phase C movement was controlled by the storage capacity (approximately 14 vehicles) of the interior approaches. During the peak period, this green time was inadequate to accommodate the frontage road demand. This resulted in a backlog of traffic on the frontage road and contributed to sluggish operation on the A and B phases.

Figures 12 and 13 show the congestion experienced during a portion of the field study. The congestion not only occurred in the intersection area as shown in Figure 12 but extended back to the exit ramps and onto the freeway (Fig. 13).

The study indicated that some of the approaches were experiencing more demand than could be accommodated. A comparison of 5-min demand volumes on the west frontage road with the number of vehicles cleared (Fig. 14) indicated that the number of vehicles forced to wait at the end of each cycle was increased by small increments until a large backlog existed.

A tabulation of cycle lengths during the peak period (Table 1) showed that the cycle lengths varied from 89 to 159 sec., with an average of 118 sec. This long cycle length imposed an excessive delay with a majority of the traffic having to wait for more than one cycle in order to clear through the interchange.

TABLE 1
BERRY I DATA

| CYCLE NO. |  | | |  | |  | | CYCLE LENGTH | TOTAL GREEN | TOTAL VEHICLES |
|-----------|---|--------------|--------------|---|------------------|---|------------------|--------------|-------------|----------------|
| | PHASE LENGTH | MOVEMENT "A" | MOVEMENT "B" | PHASE LENGTH | VEHICLE MOVEMENT | PHASE LENGTH | VEHICLE MOVEMENT | | | |
| 1 | 25 | 21 | 8 | 29 | 23 | 37 | 40 | 116 | 91 | 92 |
| 2 | 25 | 25 | 12 | 27 | 20 | 32 | 32 | 109 | 84 | 89 |
| 3 | 28 | 19 | 8 | 22 | 12 | 31 | 32 | 106 | 81 | 71 |
| 4 | 24 | 16 | 9 | 27 | 21 | 41 | 45 | 117 | 92 | 91 |
| 5 | 25 | 22 | 12 | 35 | 36 | 32 | 37 | 117 | 92 | 107 |
| 6 | 23 | 24 | 17 | 49 | 40 | 34 | 34 | 131 | 106 | 115 |
| 7 | 29 | 25 | 12 | 46 | 38 | 27 | 24 | 127 | 102 | 99 |
| 8 | 27 | 15 | 12 | 38 | 35 | 26 | 21 | 116 | 91 | 83 |
| 9 | 25 | 12 | 11 | 13 | 13 | 26 | 26 | 89 | 64 | 62 |
| 10 | 25 | 14 | 10 | 21 | 20 | 22 | 22 | 93 | 68 | 66 |
| 11 | 27 | 18 | 12 | 31 | 22 | 26 | 24 | 109 | 84 | 76 |
| 12 | 26 | 21 | 8 | 29 | 24 | 30 | 26 | 110 | 85 | 79 |
| 13 | 26 | 22 | 14 | 33 | 24 | 28 | 27 | 112 | 87 | 87 |
| 14 | 26 | 24 | 3 | 19 | 15 | 24 | 19 | 94 | 69 | 61 |
| 15 | 25 | 20 | 10 | 25 | 17 | 34 | 32 | 109 | 84 | 79 |
| 16 | 26 | 24 | 6 | 31 | 27 | 27 | 21 | 109 | 84 | 78 |
| 17 | 27 | 15 | 3 | 24 | 28 | 29 | 23 | 105 | 80 | 69 |
| 18 | 20 | 21 | 11 | 31 | 18 | 29 | 23 | 105 | 80 | 73 |
| 19 | 26 | 23 | 14 | 17 | 14 | 39 | 34 | 107 | 82 | 85 |
| 20 | 27 | 23 | 11 | 31 | 37 | 27 | 23 | 110 | 85 | 94 |
| 21 | 28 | 26 | 15 | 40 | 36 | 31 | 30 | 124 | 99 | 107 |
| 22 | 29 | 22 | 11 | 27 | 22 | 33 | 38 | 114 | 89 | 93 |
| 23 | 25 | 35 | 8 | 55 | 42 | 35 | 41 | 141 | 115 | 126 |
| 24 | 29 | 26 | 11 | 21 | 7 | 29 | 26 | 104 | 79 | 70 |
| 25 | 32 | 31 | 10 | 54 | 51 | 35 | 27 | 146 | 121 | 119 |
| 26 | 29 | 28 | 15 | 47 | 43 | 32 | 29 | 133 | 108 | 115 |
| 27 | 32 | 24 | 18 | 50 | 44 | 25 | 22 | 132 | 107 | 108 |
| 28 | 29 | 16 | 14 | 33 | 29 | 18 | 18 | 105 | 80 | 77 |
| 29 | 25 | 23 | 12 | 31 | 25 | 31 | 22 | 112 | 87 | 82 |
| 30 | 23 | 31 | 11 | 47 | 40 | 27 | 22 | 122 | 97 | 104 |
| 31 | 27 | 32 | 7 | 31 | 19 | 36 | 27 | 119 | 94 | 85 |
| 32 | 30 | 30 | 8 | 44 | 36 | 37 | 32 | 136 | 111 | 106 |
| 33 | 30 | 33 | 11 | 64 | 50 | 40 | 44 | 159 | 134 | 138 |
| 34 | 30 | 26 | 12 | 21 | 18 | 28 | 24 | 104 | 79 | 80 |
| 35 | 29 | 26 | 14 | 40 | 39 | 50 | 47 | 144 | 119 | 126 |
| 36 | 26 | 35 | 8 | 36 | 38 | 32 | 36 | 119 | 94 | 117 |
| 37 | 31 | 27 | 12 | 42 | 35 | 23 | 21 | 121 | 96 | 95 |
| 38 | 27 | 28 | 15 | 51 | 44 | 26 | 22 | 129 | 104 | 109 |
| 39 | 28 | 31 | 10 | 35 | 31 | 35 | 30 | 123 | 98 | 102 |
| 40 | 31 | 26 | 12 | 60 | 53 | 42 | 39 | 158 | 133 | 130 |
| 41 | 29 | 29 | 10 | 38 | 39 | 34 | 33 | 126 | 101 | 111 |
| 42 | 31 | 18 | 12 | 38 | 42 | 26 | 21 | 120 | 95 | 93 |
| 43 | 26 | 26 | 8 | 43 | 37 | 33 | 33 | 127 | 102 | 104 |
| 44 | 29 | 28 | 7 | 30 | 31 | 29 | 32 | 113 | 88 | 98 |
| 45 | 25 | 28 | 5 | 24 | 18 | 31 | 23 | 105 | 80 | 74 |
| 46 | 29 | 19 | 5 | 17 | 14 | 23 | 22 | 94 | 69 | 60 |
| 47 | 28 | 17 | 9 | 39 | 23 | 30 | 23 | 122 | 97 | 72 |
| 48 | 30 | 30 | 12 | 40 | 38 | 27 | 20 | 122 | 97 | 100 |
| 49 | 27 | 27 | 14 | 39 | 35 | 21 | 24 | 112 | 87 | 100 |
| 50 | 28 | 29 | 13 | 15 | 11 | 23 | 23 | 91 | 66 | 76 |

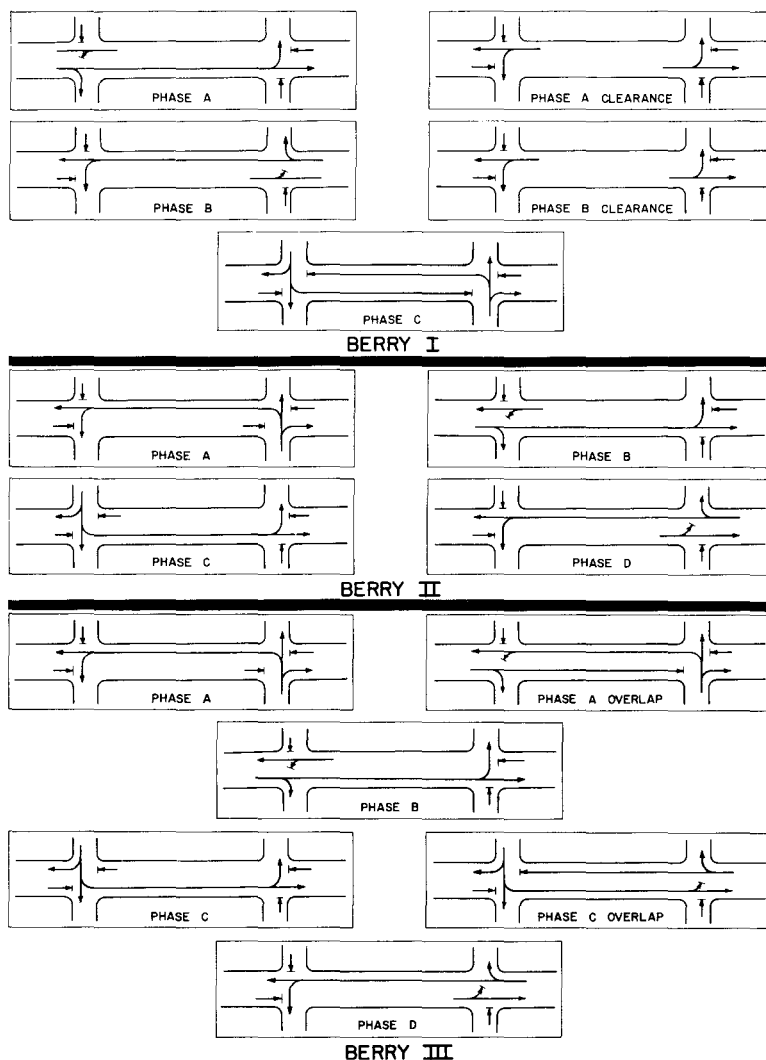


Figure 11. Phasing sequences.

Berry II: Four-Phase Operation, No Overlaps

After completion of the Berry I study, a different phasing and control system was installed at the Berry Street interchange. The three-phase controller was replaced by a two-phase volume-density controller with two minor movement controllers. The minor movement controllers were used to control the frontage road traffic, and the signal system operated with the four-phase sequence shown in Figure 11.

This phasing arrangement eliminated the storage problem and congestion that occurred with the existing three-phase system (Berry I). With this sequence, traffic on each approach was permitted to clear through the entire interchange upon receiving a green indication, and the green time was also allotted to each approach on the basis of traffic demand.

The results of the study indicated that the four-phase system was capable of handling the traffic demand at the interchange with a moderate degree of efficiency. Two approaches had backlogs of vehicles for several cycles during the study, but no serious congestion was experienced.

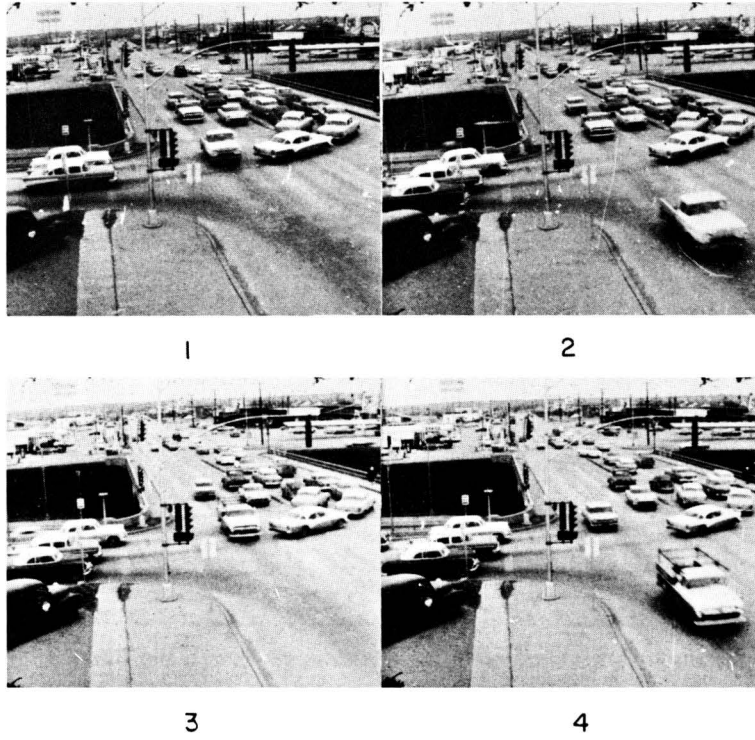


Figure 12. Congestion at intersection.

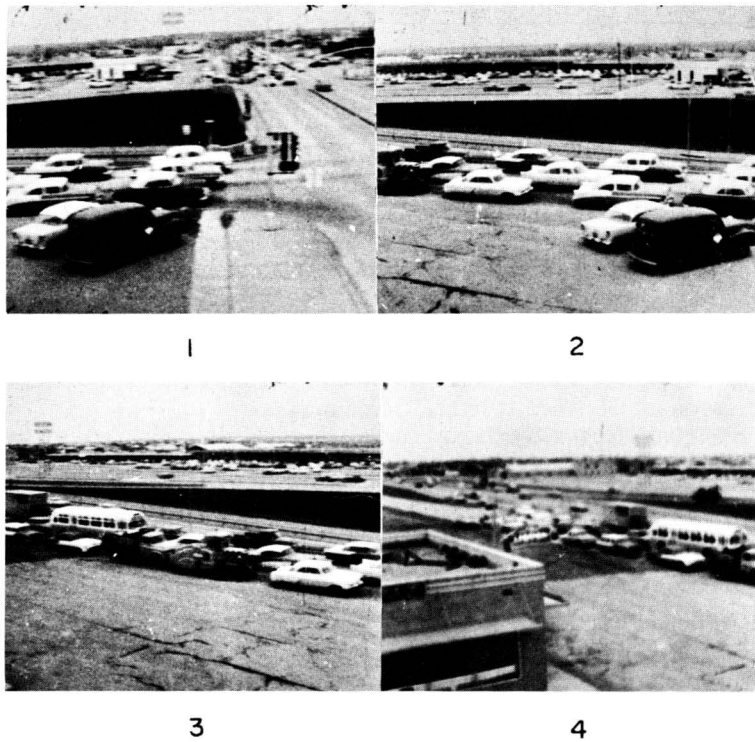


Figure 13. Congestion of ramp.

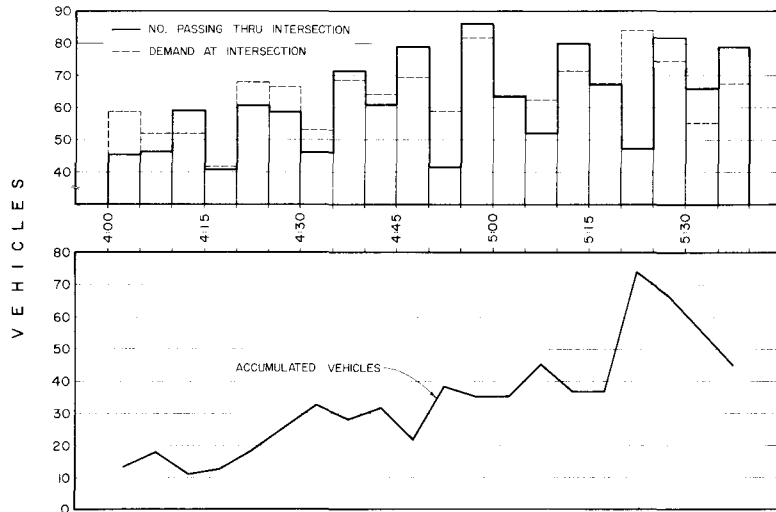


Figure 14. Accumulation of traffic demand.

The greatest disadvantage of the four-phase system was the long cycle lengths which occurred during the peak period. Table 2 gives the cycle and phase lengths recorded during the study. The cycle lengths ranged from 76 to 149 sec with an average of 105 sec. Although this average cycle length was considered to be excessive, it represented a 10 percent decrease over that obtained in the Berry I study.

Berry III: Four-Phase Operation with Overlap

The third study conducted at the Berry Street interchange evaluated operations with the recommended phasing arrangement shown in Figure 11. This phasing differed from that used in the Berry II study in that two overlap units were added to provide for an overlap of the traffic movements on the frontage road and major street approaches. The time required to move the major street traffic (starting delay plus travel time) from one approach to the other and the amber time required to terminate the frontage road movement were wasted by the sequence used in the Berry II study. By utilizing this wasted time, increased efficiency was obtained by the Berry III sequence.

Initially, it was reasoned that an effective overlap would be very difficult to obtain with actuated equipment. This was due to the fact that effective use of the overlap depended on initiating the major street green while there was still considerable traffic on the opposite frontage road. However, the overlap was accomplished very satisfactorily with the actuated control equipment by use of its variable settings for termination of a green phase in accordance with traffic demand.

Traffic movements on the frontage road were controlled by a minor movement controller as in the Berry II study. After the initiation of a frontage road green, a time gap in traffic less than the minimum vehicle interval (as set on the control unit) caused the signal control to pass to an overlap timing unit. This unit accomplished the following:

1. It terminated the left turn arrow at the opposite interior approach.
2. It initiated the major street green.
3. It timed a fixed overlap.

At the completion of this overlap phase, the frontage road green was terminated. When a frontage road movement "gapped out," the overlap timer provided an additional 5 sec of green for the frontage road movement. This feature permitted a very

low setting of the vehicle interval dial on the minor movement controllers (approximately 2 sec) and provided an efficient overlap of the frontage road and major street traffic. With the 2-sec allowable gap on the frontage road, an extension of the green indication required a closely spaced platoon of vehicles. As soon as this platoon passed the frontage road detectors, the controller "gapped out" and initiated the major street green. The additional green time provided for the frontage road movement by the overlap unit was usually sufficient to clear all "stragglers" on the frontage road approaches. If there was no traffic on a frontage road approach during the overlap phase, no time was wasted because the major street green had already been initiated.

The study indicated that the addition of the overlap units greatly increased the efficiency of operation at the interchange. The cycle lengths during the study period varied from 58 to 107 sec with an average cycle length of 77 sec (Table 3). This average cycle

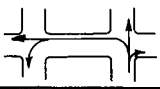
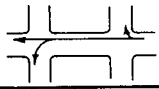


TABLE 2
BERRY II DATA

| CYCLE NO. | | | | | | | | | CYCLE LENGTH | TOTAL GREEN | TOTAL VEHICLES |
|-----------|--------------|------------------|--------------|------------------|--------------|------------------|--------------|------------------|--------------|-------------|----------------|
| | PHASE LENGTH | VEHICLE MOVEMENT | PHASE LENGTH | VEHICLE MOVEMENT | PHASE LENGTH | VEHICLE MOVEMENT | PHASE LENGTH | VEHICLE MOVEMENT | | | |
| 1 | 21 | 18 | 21 | 10 | 25 | 22 | 14 | 9 | 89 | 81 | 52 |
| 2 | 21 | 17 | 21 | 16 | 28 | 27 | 14 | 8 | 92 | 84 | 68 |
| 3 | 22 | 18 | 31 | 25 | 33 | 36 | 25 | 13 | 118 | 111 | 92 |
| 4 | 31 | 31 | 24 | 18 | 26 | 27 | 20 | 8 | 109 | 101 | 84 |
| 5 | 19 | 19 | 35 | 17 | 24 | 24 | 24 | 12 | 110 | 102 | 72 |
| 6 | 23 | 28 | 27 | 23 | 43 | 46 | 10 | 5 | 111 | 103 | 102 |
| 7 | 24 | 28 | 16 | 14 | 32 | 37 | 30 | 18 | 111 | 102 | 97 |
| 8 | 21 | 23 | 23 | 22 | 36 | 38 | 14 | 12 | 104 | 94 | 95 |
| 9 | 24 | 17 | 33 | 24 | 17 | 17 | 28 | 14 | 110 | 102 | 72 |
| 10 | 23 | 27 | 17 | 17 | 33 | 34 | 12 | 5 | 93 | 85 | 83 |
| 11 | 27 | 31 | 28 | 22 | 29 | 27 | 27 | 11 | 119 | 111 | 91 |
| 12 | 25 | 23 | 18 | 16 | 23 | 23 | 14 | 7 | 88 | 80 | 69 |
| 13 | 16 | 13 | 18 | 15 | 26 | 14 | 10 | 3 | 78 | 70 | 45 |
| 14 | 21 | 16 | 29 | 25 | 22 | 15 | 15 | 9 | 96 | 87 | 65 |
| 15 | 27 | 22 | 26 | 23 | 24 | 23 | 17 | 10 | 102 | 94 | 78 |
| 16 | 28 | 24 | 29 | 25 | 19 | 21 | 10 | 3 | 94 | 86 | 73 |
| 17 | 23 | 24 | 10 | 7 | 22 | 20 | 18 | 8 | 82 | 73 | 59 |
| 18 | 25 | 20 | 15 | 19 | 30 | 28 | 22 | 10 | 109 | 92 | 77 |
| 19 | 20 | 26 | 27 | 17 | 28 | 35 | 24 | 14 | 108 | 99 | 92 |
| 20 | 23 | 23 | 31 | 32 | 41 | 40 | 14 | 7 | 111 | 109 | 102 |
| 21 | 23 | 20 | 20 | 18 | 32 | 28 | 28 | 16 | 111 | 103 | 82 |
| 22 | 30 | 35 | 38 | 40 | 26 | 29 | 13 | 7 | 115 | 107 | 111 |
| 23 | 25 | 32 | 20 | 19 | 27 | 27 | 29 | 11 | 107 | 101 | 89 |
| 24 | 34 | 41 | 28 | 26 | 25 | 26 | 27 | 16 | 125 | 114 | 109 |
| 25 | 29 | 37 | 30 | 27 | 26 | 32 | 30 | 14 | 123 | 115 | 110 |
| 26 | 35 | 42 | 37 | 37 | 41 | 37 | 13 | 6 | 134 | 126 | 122 |
| 27 | 20 | 19 | 37 | 44 | 25 | 20 | 28 | 16 | 119 | 110 | 99 |
| 28 | 26 | 32 | 23 | 21 | 29 | 32 | 14 | 7 | 101 | 92 | 92 |
| 29 | 24 | 22 | 38 | 26 | 30 | 38 | 16 | 6 | 116 | 108 | 92 |
| 30 | 23 | 30 | 13 | 9 | 26 | 19 | 14 | 7 | 85 | 76 | 65 |
| 31 | 23 | 20 | 33 | 22 | 21 | 22 | 10 | 5 | 94 | 87 | 69 |
| 32 | 21 | 20 | 23 | 20 | 25 | 19 | 22 | 12 | 99 | 91 | 71 |
| 33 | 19 | 18 | 20 | 18 | 25 | 16 | 10 | 3 | 83 | 74 | 55 |
| 34 | 17 | 16 | 22 | 18 | 25 | 18 | 29 | 18 | 103 | 93 | 70 |
| 35 | 25 | 24 | 24 | 23 | 19 | 12 | 25 | 15 | 100 | 93 | 74 |
| 36 | 21 | 23 | 21 | 22 | 27 | 19 | 10 | 7 | 87 | 79 | 71 |
| 37 | 26 | 20 | 19 | 17 | 24 | 23 | 20 | 13 | 97 | 89 | 73 |
| 38 | 24 | 22 | 38 | 37 | 26 | 28 | 30 | 12 | 126 | 118 | 99 |
| 39 | 30 | 38 | 37 | 41 | 22 | 26 | 19 | 13 | 115 | 108 | 118 |
| 40 | 41 | 52 | 38 | 34 | 34 | 35 | 28 | 14 | 149 | 141 | 135 |
| 41 | 33 | 52 | 20 | 18 | 28 | 28 | 19 | 11 | 106 | 100 | 109 |
| 42 | 26 | 28 | 31 | 24 | 27 | 27 | 17 | 6 | 109 | 101 | 85 |
| 43 | 30 | 28 | 30 | 25 | 16 | 16 | 19 | 9 | 102 | 95 | 78 |
| 44 | 27 | 29 | 38 | 30 | 34 | 34 | 30 | 15 | 137 | 129 | 108 |
| 45 | 22 | 27 | 25 | 24 | 38 | 41 | 19 | 11 | 111 | 104 | 103 |
| 46 | 21 | 22 | 16 | 17 | 33 | 29 | 12 | 5 | 91 | 82 | 73 |
| 47 | 27 | 28 | 31 | 28 | 16 | 16 | 20 | 7 | 104 | 94 | 79 |
| 48 | 21 | 24 | 15 | 12 | 23 | 28 | 10 | 4 | 76 | 69 | 68 |
| 49 | 15 | 8 | 23 | 22 | 16 | 15 | 18 | 9 | 79 | 72 | 54 |

length was a 26.7 percent reduction from that recorded in the Berry II study and a 31.6 percent reduction from that recorded in the Berry I study.

In addition to reducing the average cycle length to a satisfactory level during the peak period, the signal system operated with a very high degree of efficiency. The actuated equipment permitted the allotment of green time to each phase in accordance with traffic demand and assured the clearance of all approaches during each cycle. The equipment also provided the flexibility to cope with unusual conditions (stalled vehicles, etc.) that occurred during the peak period.

TABLE 3
BERRY III DATA

| CYCLE NO. |  | |  | |  | |  | | CYCLE LENGTH | TOTAL GREEN | TOTAL VEHICLES |
|-----------|---|------------------|---|------------------|---|------------------|---|------------------|--------------|-------------|----------------|
| | PHASE LENGTH | VEHICLE MOVEMENT | PHASE LENGTH | VEHICLE MOVEMENT | PHASE LENGTH | VEHICLE MOVEMENT | PHASE LENGTH | VEHICLE MOVEMENT | | | |
| 1 | 15 | 7 | 20 | 14 | 14 | 14 | 16 | 5 | 64 | 65 | 40 |
| 2 | 16 | 8 | 27 | 20 | 14 | 9 | 20 | 14 | 73 | 77 | 51 |
| 3 | 15 | 7 | 23 | 15 | 22 | 19 | 25 | 21 | 80 | 85 | 62 |
| 4 | 19 | 8 | 21 | 20 | 17 | 11 | 20 | 21 | 76 | 77 | 60 |
| 5 | 15 | 5 | 22 | 18 | 25 | 15 | 23 | 16 | 80 | 85 | 54 |
| 6 | 15 | 6 | 25 | 25 | 25 | 24 | 25 | 30 | 86 | 90 | 85 |
| 7 | 15 | 6 | 21 | 24 | 14 | 10 | 22 | 21 | 68 | 72 | 61 |
| 8 | 16 | 6 | 18 | 14 | 20 | 13 | 18 | 10 | 67 | 72 | 43 |
| 9 | 17 | 7 | 19 | 14 | 14 | 10 | 26 | 28 | 72 | 76 | 59 |
| 10 | 18 | 8 | 30 | 25 | 14 | 14 | 46 | 37 | 102 | 108 | 84 |
| 11 | 15 | 11 | 19 | 19 | 23 | 18 | 36 | 35 | 90 | 93 | 83 |
| 12 | 22 | 11 | 30 | 31 | 25 | 15 | 35 | 32 | 107 | 112 | 89 |
| 13 | 15 | 9 | 30 | 27 | 25 | 18 | 32 | 28 | 97 | 102 | 82 |
| 14 | 23 | 12 | 18 | 21 | 24 | 11 | 16 | 19 | 79 | 81 | 63 |
| 15 | 17 | 8 | 31 | 26 | 22 | 17 | 25 | 22 | 91 | 95 | 73 |
| 16 | 15 | 6 | 20 | 13 | 15 | 11 | 24 | 17 | 68 | 74 | 47 |
| 17 | 15 | 8 | 15 | 12 | 14 | 7 | 20 | 15 | 59 | 64 | 42 |
| 18 | 15 | 5 | 16 | 8 | 14 | 6 | 27 | 17 | 67 | 72 | 36 |
| 19 | 17 | 7 | 20 | 14 | 22 | 17 | 14 | 13 | 71 | 73 | 51 |
| 20 | 15 | 5 | 18 | 16 | 14 | 12 | 18 | 15 | 61 | 65 | 48 |
| 21 | 15 | 4 | 19 | 11 | 14 | 13 | 22 | 16 | 65 | 70 | 44 |
| 22 | 15 | 9 | 19 | 13 | 15 | 10 | 19 | 13 | 63 | 68 | 45 |
| 23 | 15 | 3 | 23 | 19 | 0 | 13 | 23 | 20 | 78 | 81 | 55 |
| 24 | 16 | 9 | 17 | 11 | 22 | 12 | 31 | 28 | 81 | 86 | 60 |
| 25 | 22 | 12 | 17 | 15 | 31 | 21 | 18 | 20 | 84 | 88 | 68 |
| 26 | 15 | 6 | 19 | 17 | 14 | 10 | 21 | 24 | 64 | 69 | 57 |
| 27 | 15 | 5 | 15 | 2 | 21 | 13 | 26 | 26 | 73 | 77 | 46 |
| 28 | 17 | 7 | 24 | 24 | 32 | 24 | 17 | 18 | 85 | 90 | 73 |
| 29 | 17 | 10 | 18 | 18 | 19 | 16 | 20 | 19 | 70 | 74 | 63 |
| 30 | 15 | 8 | 18 | 15 | 16 | 12 | 18 | 13 | 62 | 67 | 48 |
| 31 | 17 | 4 | 22 | 23 | 17 | 18 | 25 | 19 | 76 | 81 | 64 |
| 32 | 15 | 6 | 15 | 6 | 18 | 17 | 15 | 12 | 58 | 63 | 41 |
| 33 | 18 | 4 | 15 | 4 | 26 | 20 | 23 | 14 | 77 | 82 | 42 |
| 34 | 15 | 1 | 15 | 8 | 33 | 23 | 20 | 21 | 79 | 83 | 53 |
| 35 | 15 | 7 | 15 | 6 | 20 | 16 | 19 | 15 | 64 | 69 | 44 |
| 36 | 22 | 12 | 25 | 32 | 15 | 14 | 12 | 21 | 76 | 74 | 79 |
| 37 | 15 | 7 | 24 | 24 | 14 | 16 | 19 | 15 | 66 | 72 | 62 |
| 38 | 22 | 8 | 21 | 22 | 32 | 30 | 22 | 24 | 92 | 97 | 84 |
| 39 | 20 | 9 | 24 | 24 | 35 | 30 | 28 | 27 | 102 | 107 | 90 |
| 40 | 17 | 9 | 21 | 20 | 23 | 15 | 24 | 26 | 82 | 85 | 70 |
| 41 | 17 | 6 | 23 | 24 | 27 | 17 | 28 | 30 | 90 | 95 | 77 |
| 42 | 15 | 3 | 19 | 22 | 24 | 21 | 18 | 10 | 71 | 76 | 56 |
| 43 | 15 | 4 | 20 | 22 | 15 | 6 | 17 | 12 | 62 | 67 | 44 |
| 44 | 17 | 5 | 22 | 15 | 18 | 14 | 17 | 7 | 69 | 74 | 41 |
| 45 | 14 | 4 | 18 | 18 | 15 | 11 | 19 | 15 | 61 | 66 | 48 |
| 46 | 15 | 6 | 17 | 8 | 22 | 15 | 34 | 23 | 83 | 88 | 52 |
| 47 | 14 | 4 | 19 | 18 | 17 | 10 | 21 | 14 | 67 | 71 | 46 |
| 48 | 15 | 5 | 23 | 21 | 15 | 12 | 19 | 28 | 67 | 72 | 66 |
| 49 | 14 | 8 | 26 | 23 | 37 | 28 | 18 | 18 | 91 | 95 | 77 |
| 50 | 18 | 10 | 21 | 30 | 30 | 26 | 19 | 18 | 83 | 88 | 84 |
| 51 | 23 | 11 | 29 | 36 | 15 | 15 | 37 | 33 | 99 | 104 | 95 |
| 52 | 14 | 3 | 17 | 10 | 30 | 26 | 31 | 27 | 88 | 92 | 66 |
| 53 | 14 | 5 | 26 | 22 | 25 | 25 | 29 | 30 | 89 | 94 | 82 |
| 54 | 17 | 8 | 21 | 28 | 33 | 24 | 19 | 17 | 85 | 90 | 77 |
| 55 | 17 | 9 | 25 | 30 | 30 | 28 | 18 | 21 | 86 | 90 | 88 |
| 56 | 14 | 6 | 27 | 27 | 18 | 13 | 18 | 8 | 73 | 77 | 54 |
| 57 | 17 | 8 | 22 | 19 | 26 | 20 | 27 | 24 | 87 | 92 | 71 |
| 58 | 15 | 4 | 16 | 14 | 35 | 25 | 31 | 27 | 91 | 97 | 70 |
| 59 | 17 | 9 | 18 | 19 | 30 | 23 | 17 | 14 | 76 | 82 | 65 |
| 60 | 14 | 5 | 29 | 29 | 17 | 11 | 24 | 20 | 80 | 84 | 65 |
| 61 | 14 | 5 | 22 | 12 | 22 | 17 | 19 | 19 | 73 | 77 | 53 |
| 62 | 19 | 6 | 15 | 12 | 20 | 14 | 16 | 15 | 61 | 70 | 47 |
| 63 | 14 | 6 | 22 | 5 | 20 | 18 | 18 | 17 | 69 | 74 | 46 |

Berry IV: Fixed-Time Operation

The fourth study conducted at the Berry Street interchange evaluated traffic operations with a fixed-time signal system. The fixed-time control was obtained by "short circuiting" some of the detector circuits and regulating the phase lengths by the "maximum time" dials on the actuated controllers. An 80-sec cycle was used with the phase lengths

TABLE 4
FIXED TIME DATA

| CYCLE NO. | | | | | | | | | CYCLE LENGTH | TOTAL GREEN | TOTAL VEHICLES |
|-----------|--------------|------------------|--------------|------------------|--------------|------------------|--------------|------------------|--------------|-------------|----------------|
| | PHASE LENGTH | VEHICLE MOVEMENT | PHASE LENGTH | VEHICLE MOVEMENT | PHASE LENGTH | VEHICLE MOVEMENT | PHASE LENGTH | VEHICLE MOVEMENT | | | |
| 1 | 21 | 13 | 23 | 20 | 19 | 4 | 23 | 12 | 80 | 86 | 49 |
| 2 | " | 18 | " | 15 | " | 6 | " | 19 | " | " | 58 |
| 3 | " | 16 | " | 22 | " | 6 | " | 15 | " | " | 59 |
| 4 | " | 10 | " | 21 | " | 7 | " | 15 | " | " | 53 |
| 5 | " | 13 | " | 18 | " | 5 | " | 20 | " | " | 56 |
| 6 | " | 16 | " | 21 | " | 11 | " | 16 | " | " | 64 |
| 7 | " | 11 | " | 30 | " | 11 | " | 17 | " | " | 69 |
| 8 | " | 16 | " | 22 | " | 7 | " | 19 | " | " | 64 |
| 9 | " | 24 | " | 29 | " | 6 | " | 9 | " | " | 68 |
| 10 | " | 15 | " | 17 | " | 5 | " | 23 | " | " | 60 |
| 11 | " | 15 | " | 20 | " | 8 | " | 20 | " | " | 63 |
| 12 | " | 18 | " | 24 | " | 9 | " | 19 | " | " | 70 |
| 13 | " | 13 | " | 23 | " | 8 | " | 14 | " | " | 58 |
| 14 | " | 15 | " | 20 | " | 9 | " | 17 | " | " | 61 |
| 15 | " | 15 | " | 19 | " | 9 | " | 14 | " | " | 57 |
| 16 | " | 10 | " | 21 | " | 10 | " | 21 | " | " | 62 |
| 17 | " | 18 | " | 27 | " | 3 | " | 12 | " | " | 60 |
| 18 | " | 8 | " | 27 | " | 6 | " | 13 | " | " | 54 |
| 19 | " | 16 | " | 19 | " | 5 | " | 19 | " | " | 59 |
| 20 | " | 18 | " | 19 | " | 7 | " | 18 | " | " | 62 |
| 21 | " | 15 | " | 19 | " | 10 | " | 9 | " | " | 53 |
| 22 | " | 12 | " | 23 | " | 11 | " | 17 | " | " | 63 |
| 23 | " | 9 | " | 22 | " | 7 | " | 9 | " | " | 47 |
| 24 | " | 20 | " | 21 | " | 7 | " | 23 | " | " | 71 |
| 25 | " | 22 | " | 19 | " | 3 | " | 25 | " | " | 69 |
| 26 | " | 20 | " | 21 | " | 5 | " | 23 | " | " | 69 |
| 27 | " | 20 | " | 19 | " | 8 | " | 21 | " | " | 68 |
| 28 | " | 23 | " | 20 | " | 9 | " | 23 | " | " | 75 |
| 29 | " | 19 | " | 23 | " | 11 | " | 13 | " | " | 66 |
| 30 | " | 10 | " | 14 | " | 4 | " | 19 | " | " | 47 |
| 31 | " | 8 | " | 20 | " | 7 | " | 22 | " | " | 57 |
| 32 | " | 15 | " | 21 | " | 6 | " | 22 | " | " | 64 |
| 33 | " | 16 | " | 17 | " | 9 | " | 32 | " | " | 74 |
| 34 | " | 17 | " | 27 | " | 10 | " | 32 | " | " | 86 |
| 35 | " | 13 | " | 18 | " | 11 | " | 22 | " | " | 64 |
| 36 | " | 20 | " | 19 | " | 8 | " | 27 | " | " | 74 |
| 37 | " | 19 | " | 21 | " | 10 | " | 20 | " | " | 70 |
| 38 | " | 16 | " | 12 | " | 7 | " | 17 | " | " | 52 |
| 39 | " | 10 | " | 18 | " | 9 | " | 15 | " | " | 52 |
| 40 | " | 20 | " | 15 | " | 6 | " | 21 | " | " | 62 |
| 41 | " | 12 | " | 13 | " | 8 | " | 17 | " | " | 50 |
| 42 | " | 16 | " | 16 | " | 17 | " | 15 | " | " | 64 |
| 43 | " | 19 | " | 12 | " | 8 | " | 17 | " | " | 56 |
| 44 | " | 20 | " | 23 | " | 3 | " | 16 | " | " | 62 |
| 45 | " | 13 | " | 23 | " | 5 | " | 9 | " | " | 50 |
| 46 | " | 7 | " | 23 | " | 9 | " | 14 | " | " | 53 |
| 47 | " | 20 | " | 18 | " | 10 | " | 14 | " | " | 52 |
| 48 | " | 20 | " | 16 | " | 6 | " | 21 | " | " | 63 |
| 49 | " | 22 | " | 19 | " | 3 | " | 15 | " | " | 59 |
| 50 | " | 18 | " | 24 | " | 6 | " | 25 | " | " | 73 |
| 51 | " | 25 | " | 17 | " | 9 | " | 20 | " | " | 71 |
| 52 | " | 18 | " | 15 | " | 4 | " | 30 | " | " | 67 |
| 53 | " | 22 | " | 11 | " | 6 | " | ? | " | " | ? |
| 54 | " | 20 | " | 22 | " | 10 | " | 29 | " | " | 81 |
| 55 | " | 21 | " | 27 | " | 4 | " | 24 | " | " | 76 |
| 56 | " | 25 | " | 27 | " | 3 | " | 33 | " | " | 88 |
| 57 | " | 18 | " | 20 | " | 10 | " | 25 | " | " | 73 |
| 58 | " | 20 | " | 16 | " | 4 | " | 21 | " | " | 61 |
| 59 | " | 20 | " | 22 | " | 5 | " | 20 | " | " | 67 |
| 60 | " | 19 | " | 16 | " | 6 | " | 17 | " | " | 58 |
| 61 | " | 20 | " | 15 | " | 11 | " | 24 | " | " | 70 |
| 62 | " | 21 | " | 17 | " | 8 | " | 24 | " | " | 70 |
| 63 | " | 18 | " | 10 | " | 12 | " | 22 | " | " | 62 |
| 64 | " | 16 | " | 22 | " | 7 | " | 25 | " | " | 70 |
| 65 | " | 14 | " | 15 | " | 6 | " | 24 | " | " | 59 |

given in Table 4. This cycle length was determined from the traffic volumes to be handled on each approach and was comparable to the average cycle length obtained in the Berry II study. The phasing arrangement used was identical to that used in the Berry III study.

The inability of the signal system to adjust to fluctuating traffic demands created long queues on some of the approaches during the peak period. This forced a number of vehicles to wait for more than one cycle and thereby caused considerable vehicular delay.

Visual observation of traffic operation during the study indicated that the system was able to accommodate the traffic demand but with a much lower degree of efficiency than obtained with the Berry III actuated system. Vehicular delays were greater, and longer queues of waiting traffic were observed on all of the approaches.

Traffic movements through the interchange appeared to approach a congested condition during most of the peak period of flow. It is believed that the occurrence of any

TABLE 5
OFF-PEAK DATA (12:00 AM - 01:00 AM)

| CYCLE NO. | | | | | | | | | TOTAL GREEN | CYCLE LENGTH | TOTAL VEHICLES |
|-----------|--------------|------------------|--------------|------------------|--------------|------------------|--------------|------------------|-------------|--------------|----------------|
| | PHASE LENGTH | VEHICLE MOVEMENT | PHASE LENGTH | VEHICLE MOVEMENT | PHASE LENGTH | VEHICLE MOVEMENT | PHASE LENGTH | VEHICLE MOVEMENT | | | |
| 1 | 17 | 0 | 0 | 0 | 34 | 1 | 14 | 3 | 65 | 69 | 4 |
| 2 | 16 | 0 | 14 | 1 | 14 | 4 | 14 | 2 | 58 | 60 | 7 |
| 3 | 16 | 0 | 14 | 1 | 12 | 1 | 14 | 3 | 56 | 57 | 5 |
| 4 | 15 | 4 | 14 | 1 | 12 | 3 | 14 | 1 | 55 | 57 | 9 |
| 5 | 16 | 2 | 0 | 0 | 7 | 2 | 12 | 3 | 35 | 30 | 7 |
| 6 | 12 | 3 | 0 | 0 | 6 | 0 | 14 | 1 | 32 | 35 | 4 |
| 7 | 15 | 1 | 14 | 1 | 12 | 4 | 14 | 2 | 55 | 57 | 8 |
| 8 | 15 | 1 | 0 | 0 | 11 | 5 | 14 | 2 | 40 | 45 | 8 |
| 9 | 16 | 1 | 0 | 0 | 6 | 2 | 14 | 2 | 36 | 41 | 5 |
| 10 | 16 | 0 | 0 | 0 | 6 | 1 | 14 | 1 | 36 | 40 | 2 |
| 11 | 21 | 1 | 0 | 0 | 6 | 1 | 0 | 0 | 27 | 35 | 2 |
| 12 | 11 | 2 | 0 | 0 | 6 | 1 | 15 | 1 | 32 | 34 | 4 |
| 13 | 15 | 1 | 15 | 1 | 13 | 3 | 15 | 1 | 58 | 56 | 6 |
| 14 | 16 | 4 | 0 | 0 | 6 | 1 | 15 | 3 | 37 | 40 | 8 |
| 15 | 17 | 5 | 0 | 0 | 6 | 0 | 0 | 0 | 23 | 31 | 5 |
| 16 | 10 | 2 | 0 | 0 | 6 | 0 | 15 | 4 | 31 | 32 | 6 |
| 17 | 16 | 3 | 0 | 0 | 10 | 3 | 15 | 3 | 41 | 43 | 9 |
| 18 | 16 | 4 | 0 | 0 | 72 | 5 | 0 | 0 | 88 | 99 | 9 |
| 19 | 8 | 2 | 0 | 0 | 7 | 1 | 0 | 0 | 15 | 22 | 3 |
| 20 | 68 | 5 | 0 | 0 | 6 | 0 | 15 | 2 | 89 | 95 | 7 |
| 21 | 16 | 0 | 0 | 0 | 6 | 4 | 15 | 2 | 37 | 40 | 6 |
| 22 | 7 | 1 | 15 | 1 | 13 | 2 | 0 | 0 | 35 | 46 | 4 |
| 23 | 9 | 3 | 0 | 0 | 6 | 0 | 16 | 1 | 31 | 31 | 4 |
| 24 | 21 | 0 | 15 | 1 | 13 | 2 | 16 | 2 | 65 | 61 | 5 |
| 25 | 17 | 1 | 0 | 0 | 36 | 3 | 16 | 1 | 69 | 69 | 5 |
| 26 | 17 | 2 | 0 | 0 | 6 | 1 | 0 | 0 | 23 | 29 | 3 |
| 27 | 9 | 0 | 15 | 0 | 13 | 0 | 17 | 4 | 54 | 50 | 4 |
| 28 | 20 | 3 | 15 | 1 | 13 | 0 | 16 | 1 | 64 | 59 | 5 |
| 29 | 17 | 4 | 0 | 0 | 6 | 1 | 16 | 1 | 39 | 39 | 6 |
| 30 | 44 | 2 | 0 | 0 | 6 | 0 | 16 | 1 | 66 | 66 | 3 |
| 31 | 17 | 0 | 0 | 0 | 6 | 0 | 16 | 7 | 39 | 40 | 7 |
| 32 | 17 | 1 | 15 | 1 | 18 | 1 | 16 | 5 | 66 | 57 | 8 |
| 33 | 17 | 1 | 15 | 2 | 14 | 2 | 16 | 3 | 62 | 58 | 8 |
| 34 | 17 | 0 | 0 | 0 | 6 | 1 | 16 | 3 | 39 | 39 | 4 |
| 35 | 24 | 3 | 15 | 0 | 13 | 0 | 16 | 3 | 68 | 64 | 6 |
| 36 | 24 | 1 | 0 | 0 | 6 | 0 | 16 | 2 | 46 | 46 | 3 |
| 37 | 17 | 1 | 0 | 0 | 11 | 1 | 16 | 2 | 44 | 43 | 4 |
| 38 | 17 | 1 | 0 | 0 | 6 | 0 | 16 | 4 | 39 | 39 | 5 |
| 39 | 17 | 2 | 15 | 1 | 13 | 2 | 16 | 2 | 61 | 57 | 7 |
| 40 | 17 | 0 | 0 | 0 | 6 | 2 | 16 | 2 | 39 | 40 | 4 |
| 41 | 17 | 1 | 0 | 0 | 6 | 0 | 16 | 2 | 39 | 40 | 3 |
| 42 | 18 | 5 | 15 | 1 | 13 | 2 | 16 | 5 | 62 | 58 | 13 |
| 43 | 17 | 2 | 0 | 0 | 6 | 0 | 16 | 1 | 39 | 39 | 3 |
| 44 | 17 | 0 | 0 | 0 | 6 | 0 | 16 | 1 | 39 | 39 | 1 |
| 45 | 17 | 0 | 0 | 0 | 6 | 5 | 16 | 3 | 39 | 39 | 8 |
| 46 | 17 | 0 | 0 | 0 | 6 | 1 | 16 | 4 | 39 | 39 | 5 |
| 47 | 17 | 2 | 16 | 1 | 13 | 2 | 16 | 2 | 62 | 57 | 7 |
| 48 | 18 | 2 | 0 | 0 | 6 | 1 | 0 | 0 | 24 | 30 | 3 |
| 49 | 14 | 2 | 0 | 0 | 6 | 0 | 16 | 3 | 36 | 37 | 5 |
| 50 | 17 | 1 | 15 | 1 | 12 | 1 | 16 | 1 | 60 | 56 | 4 |
| 51 | 17 | 3 | 0 | 0 | 75 | 4 | 0 | 0 | 92 | 97 | 7 |
| 52 | 15 | 4 | 0 | 0 | 7 | 0 | 16 | 1 | 38 | 37 | 5 |
| 53 | 22 | 2 | 0 | 0 | 8 | 1 | 16 | 2 | 46 | 46 | 5 |
| 54 | 18 | 1 | 0 | 0 | 11 | 3 | 16 | 2 | 45 | 44 | 6 |
| 55 | 17 | 2 | 15 | 0 | 13 | 0 | 16 | 1 | 61 | 56 | 3 |
| 56 | 22 | 2 | 15 | 0 | 22 | 2 | 16 | 1 | 75 | 70 | 5 |
| 57 | 51 | 0 | 0 | 0 | 6 | 0 | 16 | 1 | 73 | 73 | 1 |

unusual condition temporarily interrupting the normal flow of traffic would have created excessive demands on all approaches. Because this system lacked the flexibility to vary cycle lengths, the congestion would have remained until the traffic demand diminished.

Off-Peak Operation

A study of off-peak operation was also conducted to evaluate the efficiency of the actuated equipment during periods of low traffic demand. This study was conducted from 12:15 to 1:00 a. m. on a Thursday. The signal control equipment was the same as that used during the Berry III study.

Data on approach volumes, cycle lengths, and phase lengths were recorded during the off-peak study (Table 5). Analysis of these data plus observations made during the study indicated that satisfactory operation could be obtained during off-peak hours.

The cycle lengths recorded during this study are not indicative of the actual operation. Because there were some cycle lengths that ranged from 50 to 97 sec, it is possible that inefficient operation occurred. However, the long cycles resulted from the equipment "dwelling" on a particular phase in the absence of traffic demand from any other approach. This did not result in inefficiency, however, because traffic on any approach was accommodated as soon as the demand was indicated.

The short cycle lengths that were recorded show the efficiency obtained. The cycle length data indicated that 25 out of 57 cycles had a length of 40 sec or less with a minimum cycle length of 22 sec. Therefore, when enough traffic was present to cause the equipment to cycle, minimum cycle lengths were observed.

Another advantage observed was the ability of the equipment to omit or "skip" phases that had no traffic demand. The data indicated that the frontage road phases were skipped 47 out of 114 times during the off-peak study.

This study revealed one possible problem that may be encountered during low-volume operation. If a vehicle desiring to make a U-turn arrives on a frontage road approach at a time when no other traffic is present at the interchange, there is a possibility that this vehicle will not clear through the entire interchange. This vehicle will be "trapped" on the interior approach while the signal remains on the following major street phase.

The off-peak studies at the Berry Street interchange indicated no "trapping" of U-turn vehicles, and it is felt that the problem of "trapping" U-turning vehicles is not as serious as it may appear. An actuation of a detector on any other approach will cause the signal to advance and release the U-turning vehicle. This problem may also be eliminated by the provision of a U-turn lane.

EVALUATION OF CONTROL EQUIPMENT

Study Results

The operational studies conducted at the Berry Street interchange provided useful data for evaluation of traffic control equipment and phasing arrangements for diamond interchange signalization. A summary of the data recorded during each of the studies is given in Tables 1 through 5.

The individual cycle lengths recorded during each study proved to be a good indication of the relative efficiency of each system. A plot of this cycle length data (Fig. 15) shows the fluctuations experienced during the four separate studies. The improved efficiency obtained during the Berry III study can be seen by comparing the cycle lengths experienced during this study with those recorded during the Berry I and Berry II studies. The Berry III study had a maximum cycle length of 107 sec and an average cycle length of 77 sec. This indicates a significant reduction in individual vehicular delay when compared with the Berry I and II studies. The Berry II study also showed an improvement over conditions existing in the Berry I study. The significance of the cycle length reduction is emphasized by the increase in efficiency and reduction in congestion observed to accompany the cycle length reduction.

Another comparison of the relative efficiency of each of the systems was made from the data presented in Table 6 which shows the total volume of vehicles moved through

the interchange during the period 4:00 to 5:20 p. m. This volume actually represents the traffic demand for this period, as it is essentially the same for all of the studies. Comparison of the total interchange volume with the average cycle length for each of the studies indicates the significant improvement in efficiency and reduction in delay obtained with the four-phase overlap system.

TABLE 6
INTERCHANGE DATA, 4 TO 5:20 PM

| Study | System | Average Cycle Length (sec.) | Interchange Volume (no.) |
|-------|-----------------|-----------------------------|--------------------------|
| I | 3-phase | 118 | 3,856 |
| II | 4-phase | 105 | 3,930 |
| III | 4-phase/overlap | 77 | 3,825 |
| IV | Fixed time | 80 | 3,778 |

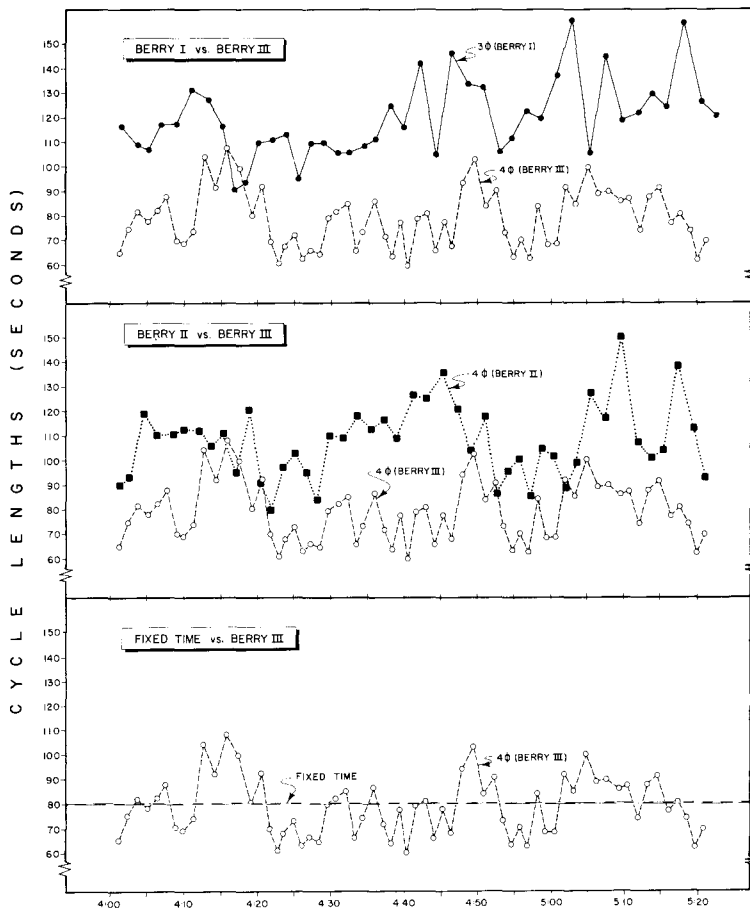


Figure 15. Cycle length comparisons.

A comparison of the Berry III cycle length plot with the 80-sec fixed-time cycle (Fig. 15) shows the inefficiency of a fixed cycle length during a peak period. The traffic-actuated equipment constantly adjusted to the varying traffic demand with a resultant variation in cycle length above and below the 80-sec fixed-time value.

A further indication of efficiency was given by a plot of the cycle lengths vs the number of vehicles moved on all approaches (Fig. 16). This plot was made more realistic by expanding the number of vehicles moved per cycle to the number of vehicles that could be moved in an hour for a given cycle length (Figure 17). It should be realized that this figure represents a hypothetical condition and shows the volume of vehicles that could be moved with each system provided there were vehicles on the

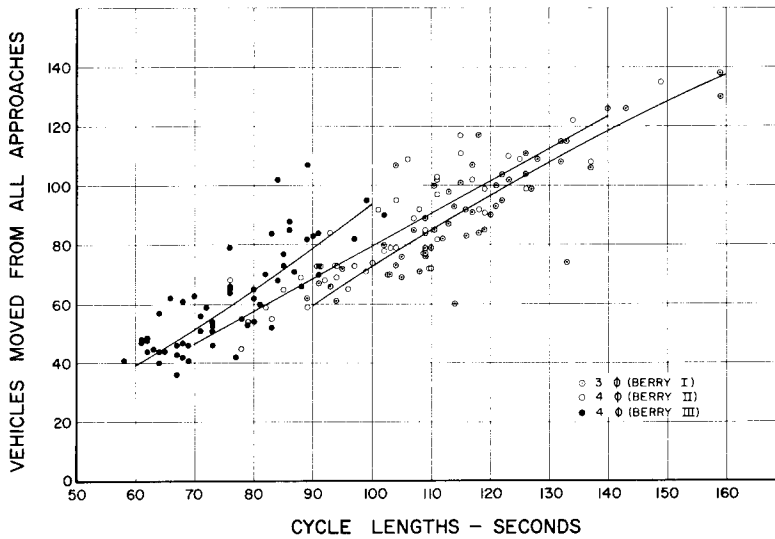


Figure 16. Plot of cycle lengths vs number of vehicles moved.

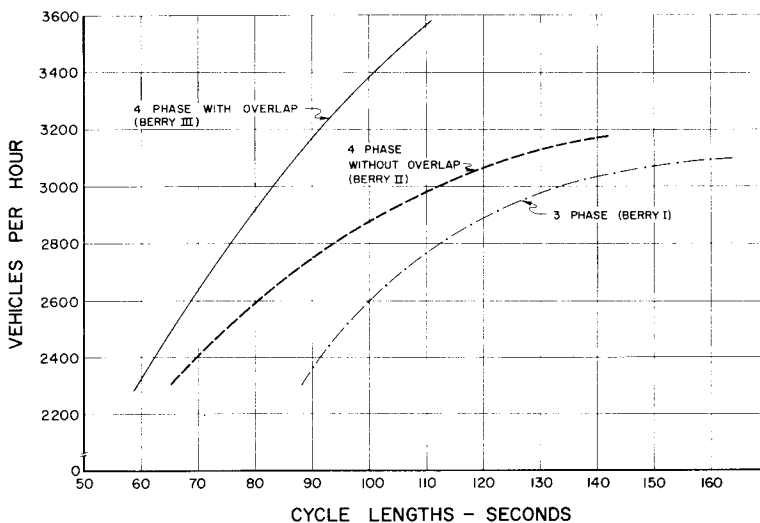


Figure 17. Plot of cycle lengths vs number of vehicles moved per hour.

approaches at all times during the hour. However, a relative measure of operation can be obtained from these curves. For example, suppose 3,000 vehicles per hr were to be moved through a diamond interchange. Referring to Figure 17, the following average cycle lengths would be required:

1. Berry III sequence, 85 sec;
2. Berry II sequence, 115 sec;
3. Berry I sequence, 134 sec.

This shows the ability of the Berry III sequence (as compared with the Berry I and Berry II sequence) to move the same traffic volume with a reduced cycle length and therefore a significant reduction in vehicular delay.

Visual observations during the studies gave the best indication of the efficiency of each of the signal systems. The congestion that occurred during the Berry I study (previously shown) was far from desirable. The peak traffic caused a breakdown of normal traffic operation on the facility and created long queues of vehicles on all approaches.

The Berry II study reflected a much more efficient operation. The vehicular movements were handled with only minor congestion during the peak hours. An actual emergency, which occurred during this study, disrupted the flow of traffic for a period of approximately 5 min and created large backlogs of traffic on all approaches. The system demonstrated its flexibility by clearing the backlog of traffic and returning to normal operation within a few cycles after the traffic disturbance was removed.

Observation of traffic movements during the Berry III study indicated operations very similar to Berry II. The shorter cycle lengths permitted more frequent green periods for each of the approaches and therefore eliminated the accumulation of long queues of vehicles. This type of operation moved the vehicles so efficiently that the peak period was not apparent to observers. This system also demonstrated the ability to adjust to unusual conditions with a minimum amount of congestion and delay.

Conclusions

The Berry Street studies completed a series of operational studies at diamond interchanges that utilized both fixed-time (Cullen and Wayside interchanges, Houston, Tex.) and traffic-actuated equipment (Berry Street interchange, Fort Worth, Tex.) It can be concluded from these studies that traffic-actuated, volume-density control equipment is the most desirable for use at signalized diamond interchanges. This conclusion is based on the following:

1. The traffic studies indicated that traffic demand at diamond interchanges fluctuates widely with respect to both individual approaches and total interchange volume. This is true of peak as well as off-peak flow. It was also observed that stalled vehicles, minor accidents, or other similar disruptions to normal traffic flow were a common occurrence during peak periods of traffic flow. These disruptions created a temporary need for increased cycle lengths in order to clear accumulated vehicles. Therefore, there was a demonstrated need for a flexible control system at diamond interchanges. If maximum operational efficiency is to be obtained, the cycle and phase lengths of the control system must be responsive to traffic demand.

2. In the past, some engineers have considered fixed-time control systems to be necessary at diamond interchanges in order to provide progressive movement for the through traffic on the major artery. Analyses of traffic movements at diamond interchanges showed that the major street through-movement represented only 20 to 30 percent of the total traffic moving through the interchange.

In view of the small percentage of through movement on the major street (as compared to total interchange volume), the provision of maximum operational efficiency for all movements through the interchange should receive primary consideration. Therefore, fixed-time systems are not warranted on the basis of providing progressive movement for major street through-traffic.

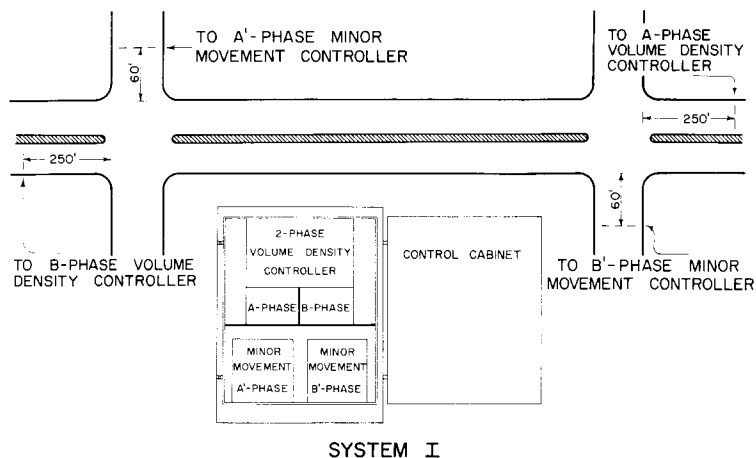
3. The Berry Street interchange studies demonstrated that actuated equipment could be adapted to provide the special sequences and overlaps required for handling diamond interchange traffic.

Control Equipment

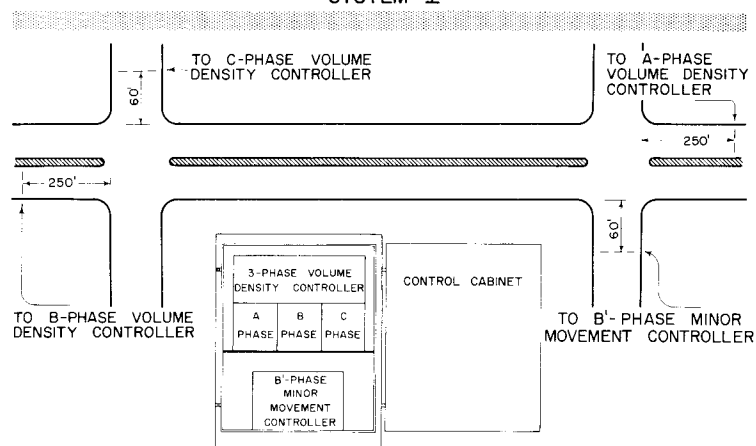
Two basic traffic control systems are recommended for conventional-type diamond interchange signalization. System I (Fig. 18) uses a two-phase volume-density controller in conjunction with two minor movement controllers. Traffic on the major street (A and B phases) is controlled by the volume-density controller, and traffic on each frontage road (A' and B' phases overlap) is controlled by a minor movement controller. In addition, special timing units are used to provide for the overlap phases.

System II (Fig. 18) uses a three-phase volume density controller in conjunction with one minor movement controller. Traffic on the major street is controlled by the A and B phases of the volume-density controller. One of the frontage road movements is controlled by the C phase of the volume-density controller, and the other frontage road movement is controlled by a minor movement controller.

The detectors for each of these systems are located as shown in Figure 18. The major street detectors are placed a minimum of 250 ft back from the stop lines. This distance is required to obtain the advantages of the volume-density features. Detectors on the the frontage roads are located 60 ft from the stop line. This allows slow moving vehicles to travel from the detectors to the intersection during the overlap time at the end of a frontage road phase and permits clearing of the frontage road approaches. This detector spacing also facilitates introduction of a U-turn lane.



SYSTEM I



SYSTEM II

Figure 18. Basic control equipment.

System II has advantages over System I in that one of the frontage road movements can be controlled with the volume-density controller. However, either of the two systems recommended will provide a highly efficient control system for a conventional-type diamond interchange.

DESIGN ASPECTS OF DIAMOND INTERCHANGES

Design Volume

In developing the studies on diamond interchanges, it was recognized that actual traffic demand must be measured in order to determine accurately the amount of traffic that should be accommodated at a signalized intersection. This can be done by counting traffic in advance of the traffic queues on each approach as shown in Figure 19. As the traffic queues lengthen, the counting line is moved so that vehicles are counted when they are still moving at approximately 10 to 15 mph. Such counts provide an accurate measure of traffic demand at intersections.

Early in the interchange studies it became evident that demand volumes fluctuate greatly during periods of peak flow. To obtain a good measure of this fluctuation, demand volumes were recorded by 5-min periods and by each signal cycle.

Figure 20 shows typical variation of traffic demand on an approach to a diamond interchange during a peak period. This fluctuation should be considered in all designs.

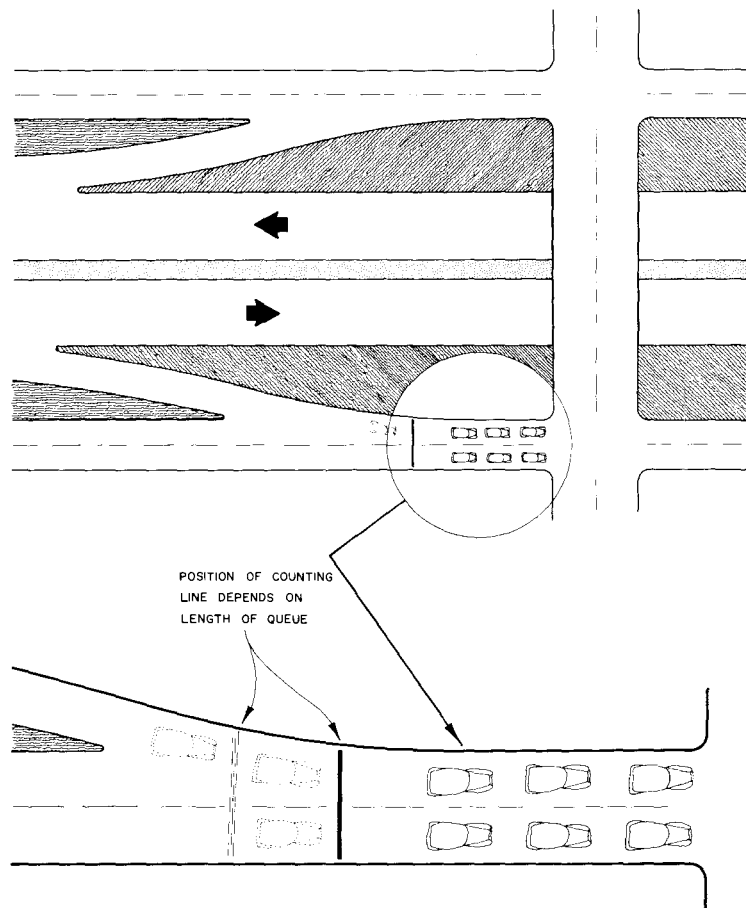


Figure 19. Procedure for determining traffic demand.

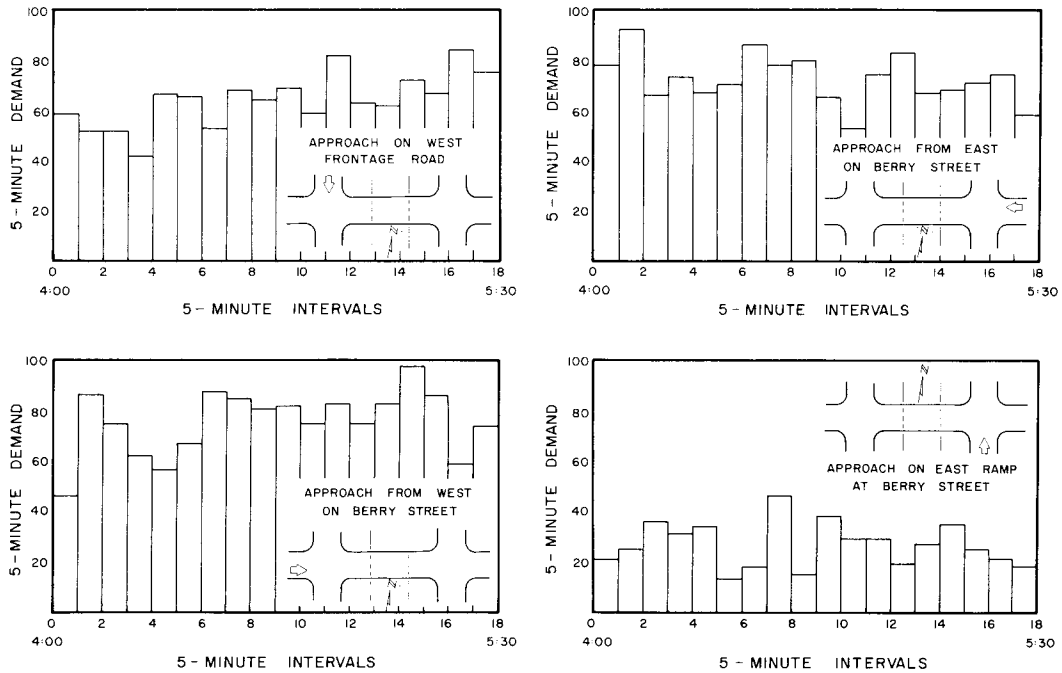


Figure 20. Demand fluctuations, Berry Street interchange, Fort Worth, Tex.

The total hourly volume is not sufficient for design because this volume is greatly exceeded during the peak 30 min of flow. Thus it becomes necessary to design on a period of less than an hour, or to adjust the hourly volume to take the peak hour fluctuations into account.

This peak hour adjustment was considered significant enough to warrant special study. A study of peak-hour traffic flow at signalized intersections was conducted and analyzed by Drew (2).

It was found that the average signalized intersection on a major artery in an urban area will experience a peak approximately 30 min in length and that 55 to 60 percent of the total hourly demand will occur during this peak 30-min period. On the basis of these studies, it was decided to increase all hourly volumes by a factor of 1.15 to obtain a proper design figure. This procedure is followed in all design examples presented in this report. Drew (2) should be consulted for a more detailed discussion of peak-hour demand fluctuation.

Lane Assignment

In working with the capacity design procedure presented in the authors' report (1), it is necessary to develop a lane assignment for the traffic volumes from each approach. Therefore, it is important that the design traffic data provide volume and turning movement information from which critical lane volumes can be determined. Studies of lane distribution at intersection approaches indicated that, in general, traffic distributes equally over the approach lanes. High-volume turning movements may require special consideration and the critical lane volume should be increased slightly to allow a factor of safety. The determination of the critical lane volumes requires a thorough study of the traffic movements on each of the approaches. No definite procedure can be established for this determination inasmuch as it is greatly dependent on engineering judgment.

After a critical lane volume is determined for an approach (based on some assumed design), this volume can be used for design because the adjacent lanes with smaller volumes will move during the same time.

Right Turn Lanes

The purpose of the diamond interchange is to move traffic between a major street and a freeway system. This interchange movement develops an inherently heavy right turn at each of the four approaches (Fig. 21). Consequently, it is important to give major consideration to these movements in the design of the interchange.

The operation of free right turn lanes at high-volume diamond interchanges has not been good and indicates that the right turn movement should be controlled by signals. Poor operation has also developed on interchanges that have inadequate turn radii for the right turn movements. Therefore, it was concluded that the right turn movement should be given special attention by a design such as that shown in Figure 22. With this design, the right turn movement is controlled by the signal but is greatly facilitated by the improved geometrics. In cases where the right turn volume is extremely heavy, provision should be made for turning two lanes simultaneously.

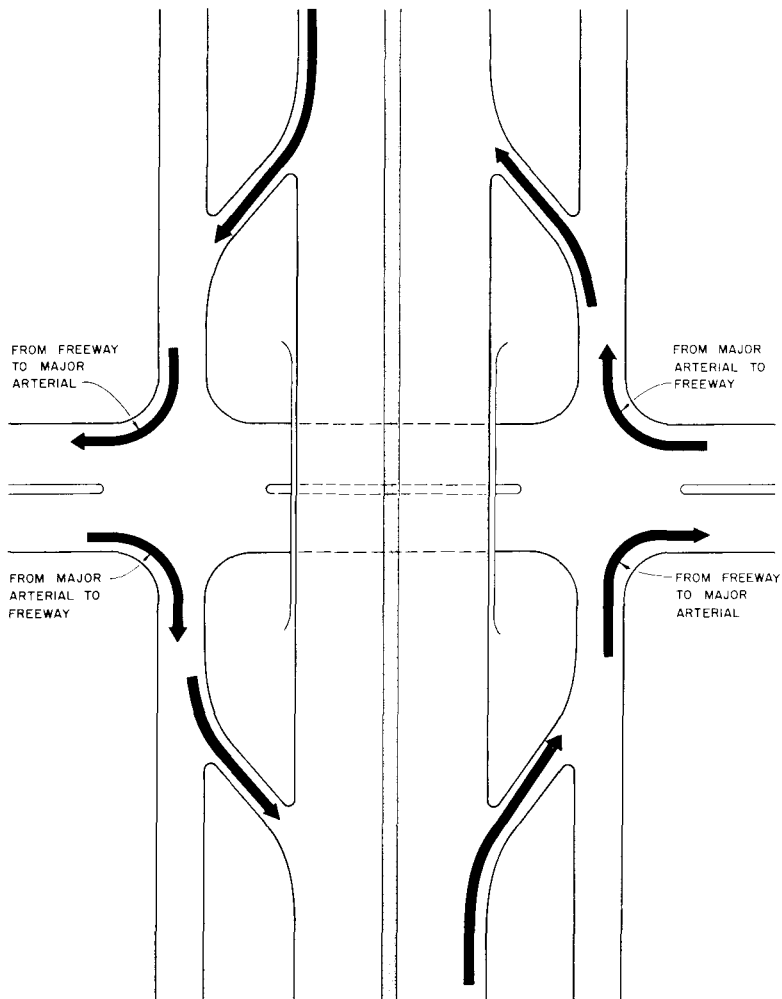


Figure 21. Interchange movements.

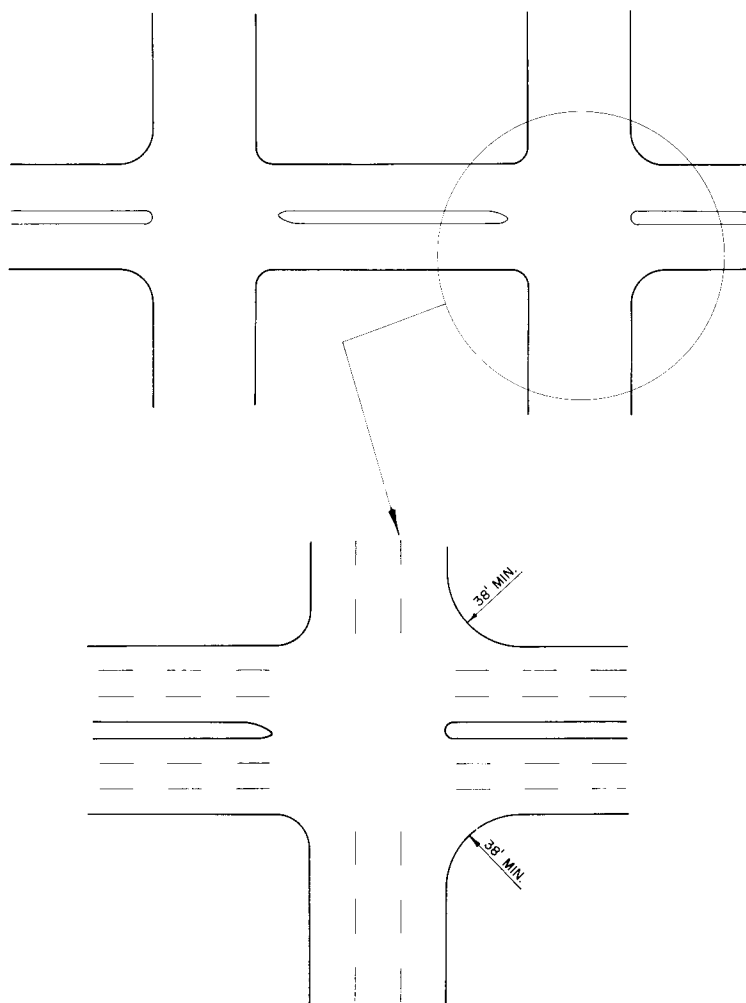


Figure 22. Desirable geometrics for right turn movements at diamond interchange.

Number of Lanes on Interior Approaches

Results of operational studies on diamond interchanges indicated that the number of lanes to be provided on the interior approaches is governed by the major street approaches. The same number of lanes should be provided on the interior approaches as will ultimately be required for the major street approaches.

Previously, there has been special consideration given to providing an additional lane on each of the interior approaches to obtain a separate left turn lane. This separate left turn lane is required if any phasing arrangement other than that shown in Figure 4 is used. This method of operation will not be satisfactory, however, if heavy left turn movements are experienced. The storage room that can be provided will not accommodate more than 7 vehicles per lane.

With the four-phase operation, left turns from the interior approaches are not critical. This is true because only U-turning vehicles arriving during the last 8 to 10 seconds of a frontage road phase are required to store on the interior approaches. Therefore, very satisfactory operation can be obtained if the same number of lanes are provided on the interior approaches as on the major street approaches.

U-Turn Lanes

A desirable feature that can be incorporated into the design of diamond interchanges is a U-turn lane. This lane provides for the free movement of traffic from one frontage road to another. This extra lane normally requires additional structure and thus additional expense. There is a question as to the justification of this additional cost.

The U-turn movement from a frontage road is the most difficult to handle of all interchange movements. This movement involves two left turns through the intersection area, and large volumes of U-turning traffic can cause a complete breakdown of traffic operation.

The warrant for a U-turn lane depends on the demand for the U-turn movement. However, a good estimate of future U-turning traffic is very difficult to predict during the design stage. The U-turn movement is created by traffic generators located ad-

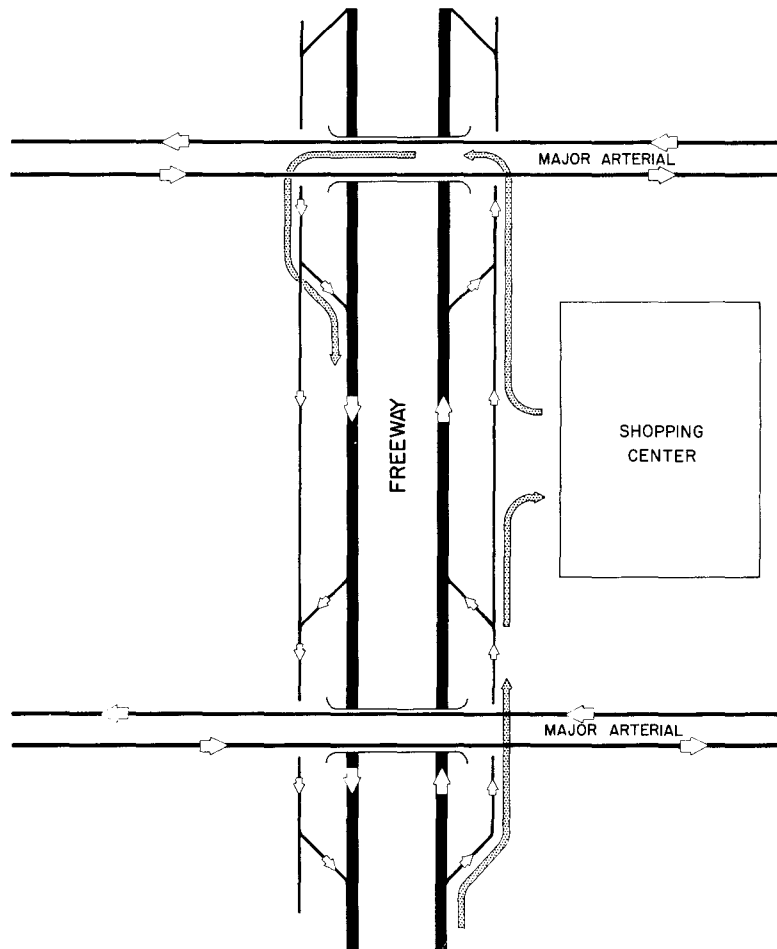


Figure 23. Generation of U-turn movements.

adjacent to the frontage roads; and the location, installation date, and impact of such generators are almost impossible to predict accurately.

An excellent example of how a heavy U-turn movement can develop is shown in Figure 22. A large shopping center is being constructed adjacent to the frontage road on IH 35W in Fort Worth, Tex. This shopping center is expected to create a very heavy traffic movement of the type shown in this figure. This will generate a heavy U-turn movement at the Seminary Drive interchange and will require a modification of this interchange. An analysis of the expected volumes and their effect on the interchange is presented in the example section of this report.

Thus, in urban areas where extensive future land development is likely to occur along the frontage roads, the provision of U-turn lanes is a relatively inexpensive measure that will insure against the interchange becoming inadequate for the developing U-turn movements which cannot be predicted.

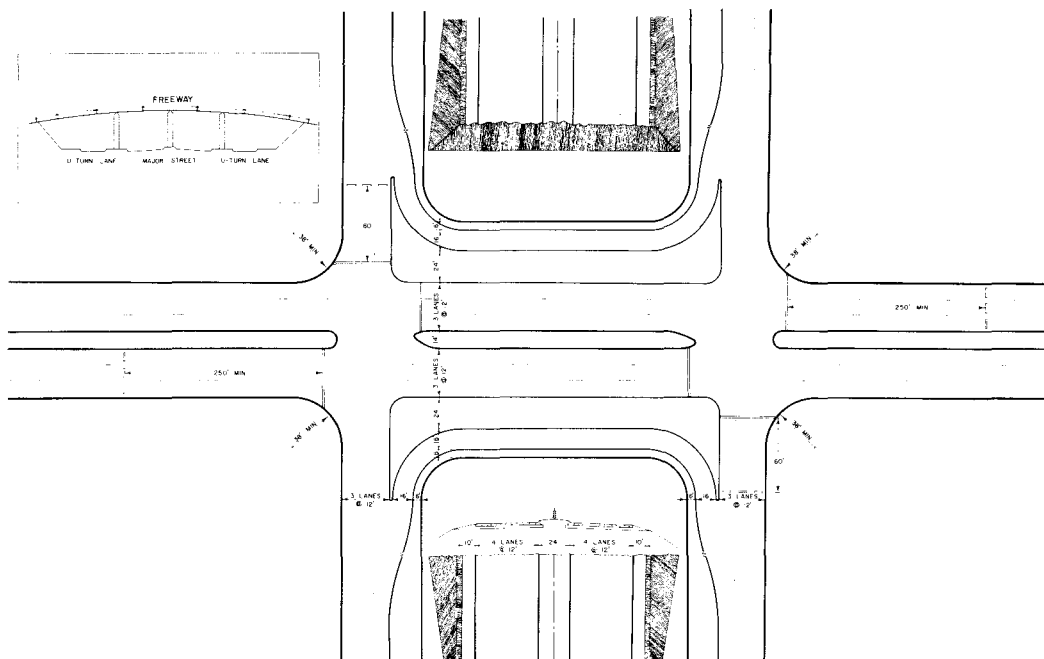


Figure 24. Desirable geometrics for conventional-type diamond interchange.

Desirable Design

Figure 24 presents a desirable design incorporating the previously discussed design factors. This design, when incorporated with the recommended traffic control equipment, will produce a highly efficient interchange. The number of lanes required on each of the approaches is a function of the design volumes and should be obtained by a capacity analysis. The geometric features (such as turn radii and island location) are applicable to a design for any number of lanes.

EXAMPLES OF DIAMOND INTERCHANGE

Regardless of the efficiency of the signal system used at diamond interchanges, satisfactory operations cannot be obtained when traffic demand exceeds the capacity of the interchange. Thus, in addition to the recommended signal controls, adequate interchange capacity must be provided by the initial design.

Many existing diamond interchanges are presently experiencing congestion with a resultant inefficiency in operation. Possible improvement could be obtained at these interchanges by a critical capacity evaluation of their present operation. Modifications of the design and/or signalization may be necessary to accommodate present or future traffic demands.

A capacity-design procedure for designing and evaluating diamond interchanges was developed and reported during the first phase of the diamond interchange studies. This report (1) is available for detailed information on diamond interchange capacity. Three examples of a capacity-design analysis for diamond interchanges are presented in this report to emphasize and explain the design procedure further.

Design of Future Interchanges

For a design example of a future interchange, the intersection of the West Loop Freeway and Richmond Road in Houston, Tex., was considered. Future ADT volume assignments for this intersection were obtained from the Houston Urban Study and are shown in Figure 25. Assuming a K-factor (percent ADT) of 10 percent and a D-factor (directional distribution) of 60 percent, the interchange volumes shown in Figure 25 were developed.

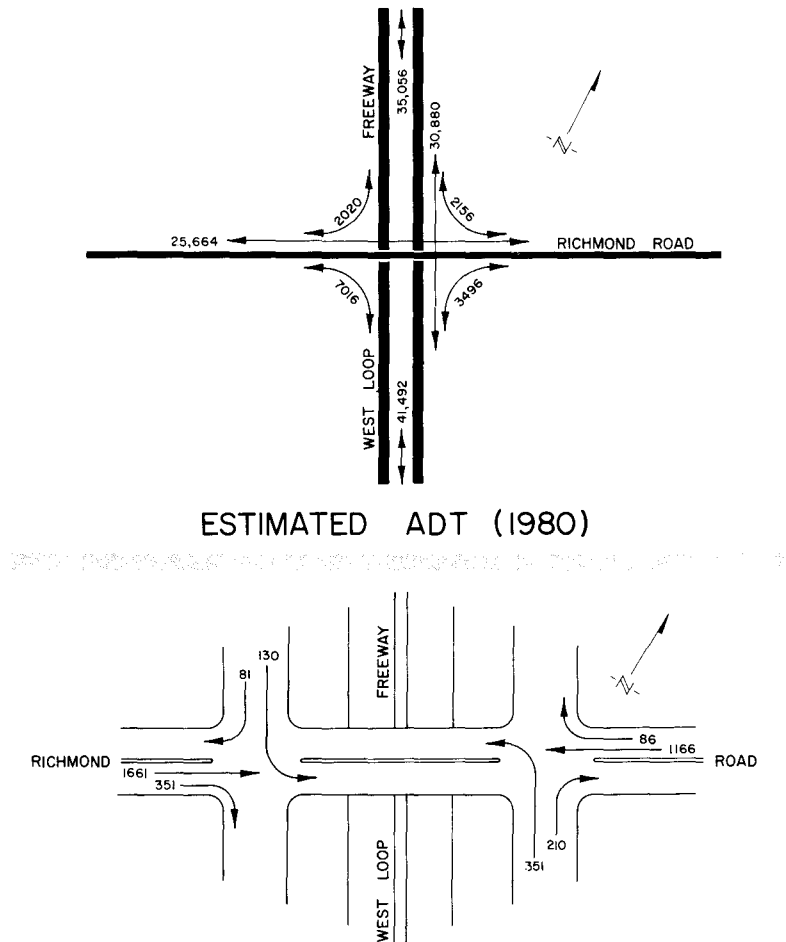


Figure 25. Estimated hourly volumes (1,980), a. m. peak.

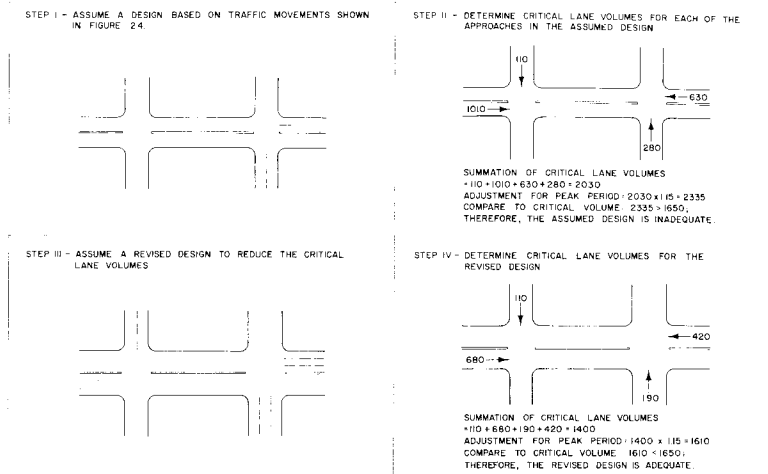
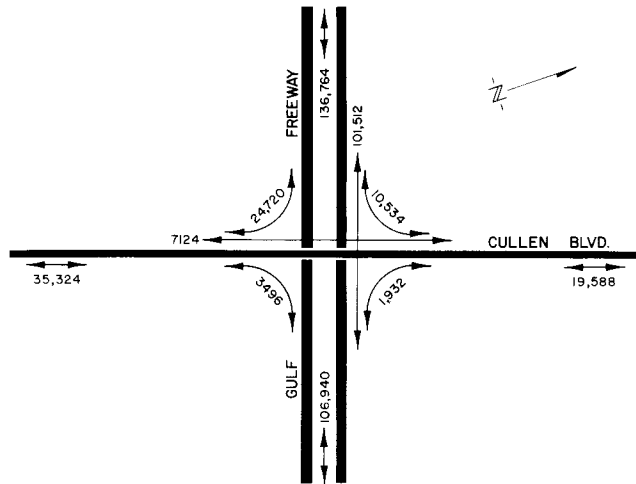


Figure 26. Sample calculations for diamond interchange, West Loop Freeway and Richmond Road, Houston, Tex.



ESTIMATED ADT (1980)

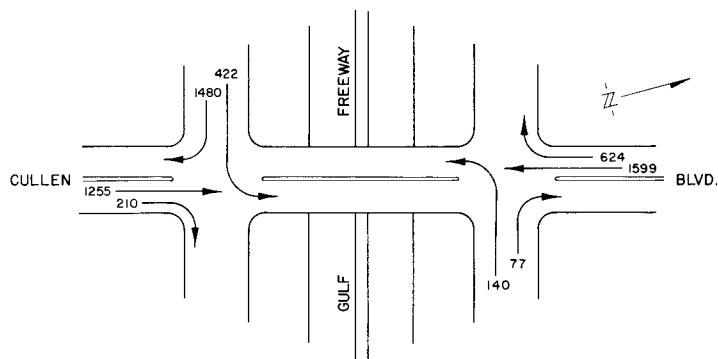


Figure 27. Estimated hourly volumes (1,980), p. m. peak.

Figure 26 shows the steps necessary to evaluate and design a conventional-type diamond interchange for use at this intersection. The calculations indicated that a conventional-type diamond interchange would be adequate for this location if the required number of approach lanes and adequate signalization were provided.

It is apparent that some interchange volumes when subjected to this type of analysis would yield unreasonable designs. Such results would indicate a higher type of direc-

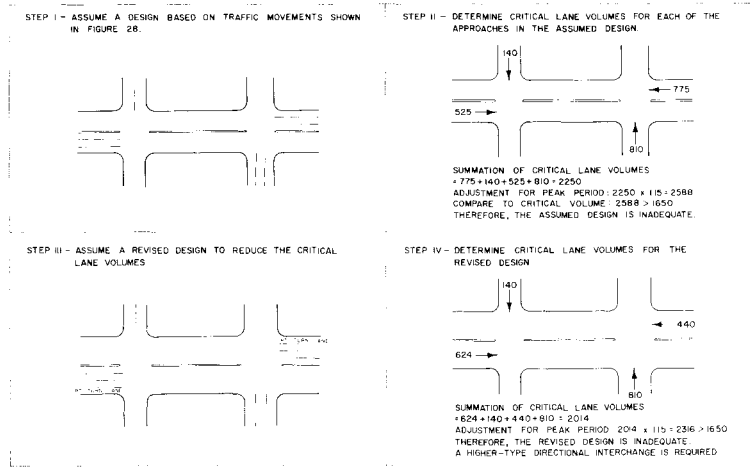


Figure 28. Sample calculations for diamond interchange, Gulf Freeway and Cullen Boulevard, Houston, Tex.

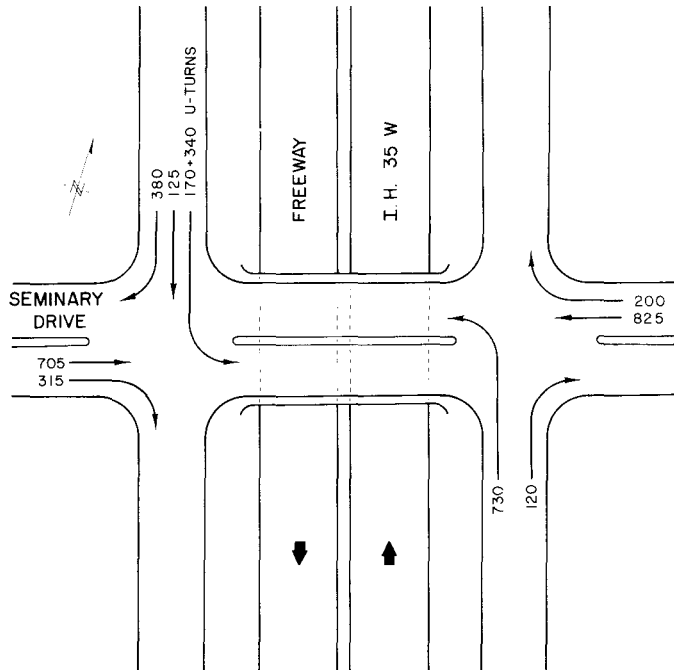


Figure 29. Estimated peak-hour volume (1,975), a. m. peak, Seminary Drive, Interstate 35W, Fort Worth, Tex.

tional interchange is warranted. An example of such a volume condition is shown in Figure 27. The analysis of these data (Fig. 28) shows that a conventional-type diamond interchange would be inadequate.

Evaluation of Existing Interchanges

The evaluation of an existing interchange is illustrated by the Seminary Drive interchange on Interstate 35W in Fort Worth, Tex. This interchange will be greatly affected by the future construction of a shopping center near the interchange, as shown in Fig. 23.

The Seminary Drive interchange is presently accommodating existing traffic volumes with little or no congestion. However, the shopping center is expected to create large U-turn movements at this interchange in the future. This is shown by the predicted volumes in Figure 29. Because there are no U-turn lanes provided at this interchange, the large U-turn movements will create congestion.

A capacity analysis for this interchange is shown in Figure 30. The modifications (indicated by this analysis) should provide the required capacity to accommodate the future traffic demand.

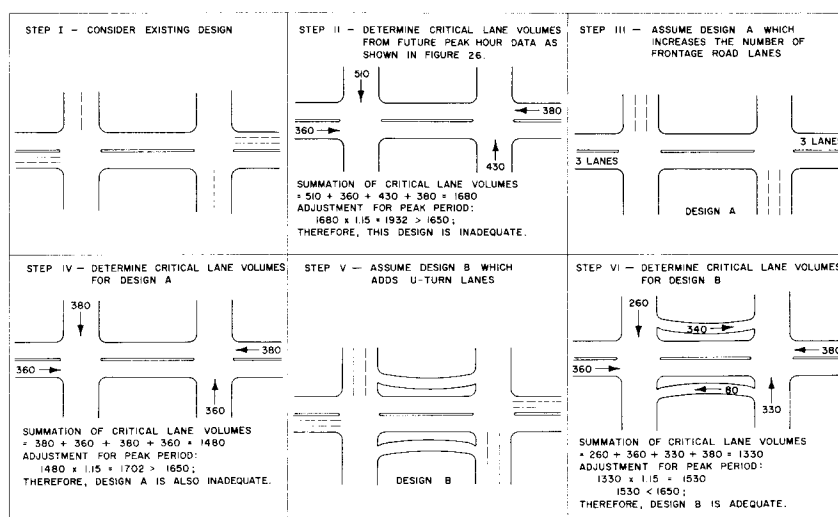


Figure 30. Seminary Drive interchange, Interstate 35W, Fort Worth, Tex.

SUMMARY

As a result of research work conducted by the Texas Transportation Institute on conventional-type diamond interchanges, it is concluded that this type of interchange has many efficient applications on freeway systems in urban areas. With adequate design and proper signalization, the diamond interchange is capable of providing a high degree of efficiency in the interchanging of major arterial and freeway traffic.

ACKNOWLEDGMENTS

Grateful acknowledgement is expressed to members of the Traffic Engineering Department of Fort Worth and the Fort Worth District of the Texas Highway Department for invaluable assistance rendered during the field studies of this project. Appreciation is also expressed to members of the staff of the Texas Transportation Institute who assisted in the collection and analysis of the field data.

REFERENCES

1. Capelle, D. G., and Pinnell, C., "Capacity Study of Signalized Diamond Interchanges." HRB Bull. 291, 1-25 (1961).
2. Drew, D. R., "An Analysis of Peak Traffic Demand at Signalized Urban Intersections." Thesis, A. & M. College of Texas (1961).
3. Leisch, J. E., "Design Geometrics for Diamond Interchanges." Proc., Inst. of Traffic Engineers (1960).
4. LeRoy, H. M., and Clinton, J. W., "Signalization of Diamond Interchanges." Proc. Inst. of Traffic Engineers (1960).
5. Moskowitz, K., "Signalizing a Diamond Interchange." Proc. Northwest Traffic Engineering Conf. (July 1959).