DESIGN AND OPERATION OF DIAMOND INTERCHANGES

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RESEARCH PUBLICATIONS ON FREEWAY OPERATIONS

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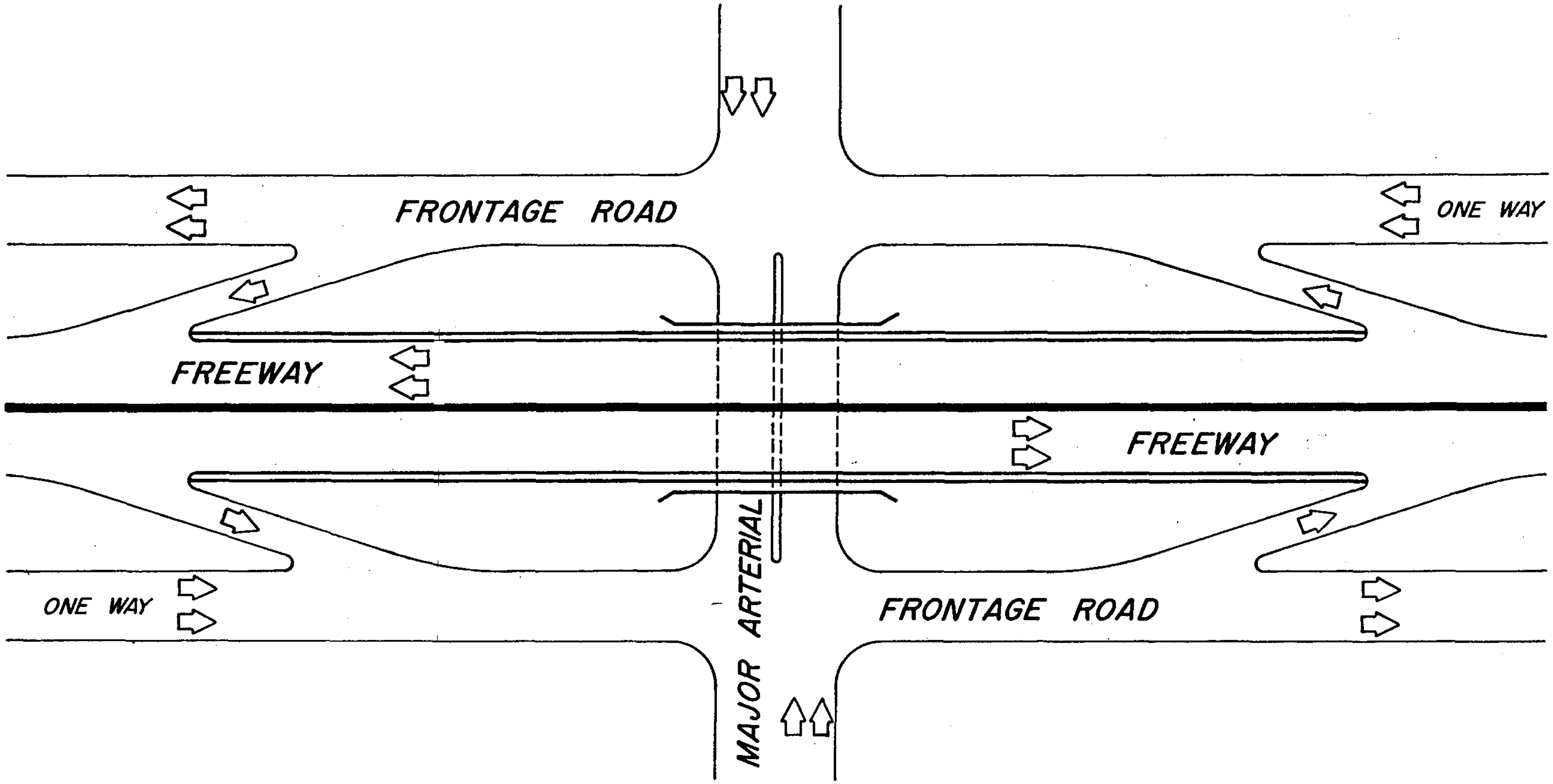
INTRODUCTION

This report is a presentation of results obtained from research studies on diamond interchanges conducted by the Texas Transportation Institute in co-operation 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 entitled "Capacity Study of Signalized Diamond Interchanges." This report was presented at the 40th annual meeting of the Highway Research Board and 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 which 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.



DIAMOND INTERCHANGE
CONVENTIONAL ARRANGEMENT

FIGURE I

INTERCHANGE TYPE

There are many design variations of the diamond interchange, and numerous conditions may exist which will affect its operation. It should be emphasized that the research studies conducted in connection with this project involved only the conventional-type diamond interchange as shown in Figure 1. 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 in this report 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.

SIGNAL OPERATIONS

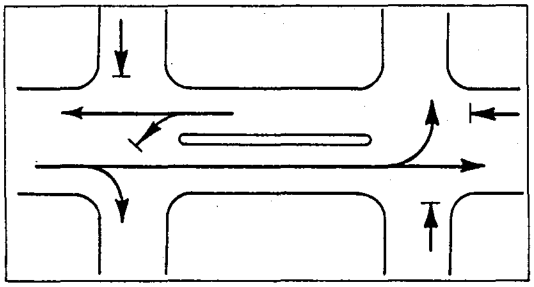
Requirements

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:

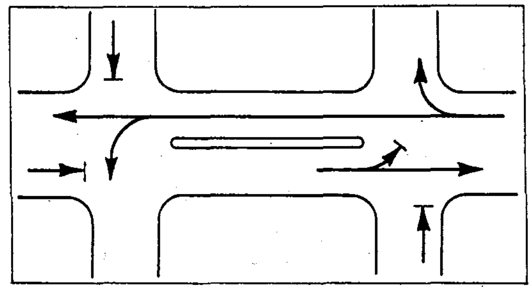
1. Separate all high-volume conflicting movements in the interchange area.
2. Minimize storing of vehicles between the two intersections.

In considering the signal system to be utilized at a diamond interchange, it is natural to assume that the type of signalization would depend upon the traffic volumes and movements experienced. Since many of the future diamond interchanges will be a part of new freeways extending into areas which are relatively undeveloped, 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 in order to accommodate the various traffic conditions which are likely to be encountered. However, this is not entirely true due to the peculiarities of diamond interchange operation.

Since the two signalized intersections of a conventional-type diamond interchange are usually spaced approximately 220 to 290 feet apart (center-to-center), two factors which influence the signal phasing are (1) amount of vehicle storage between the two intersections and (2) 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 since only one lane is generally available for the storage of left turning vehicles.



PHASE A



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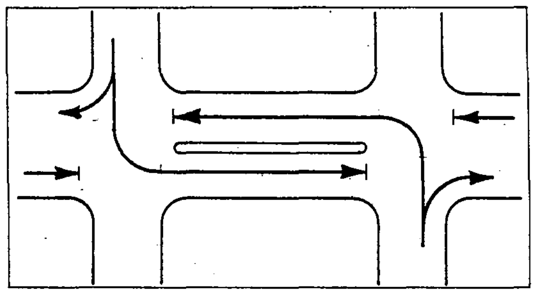
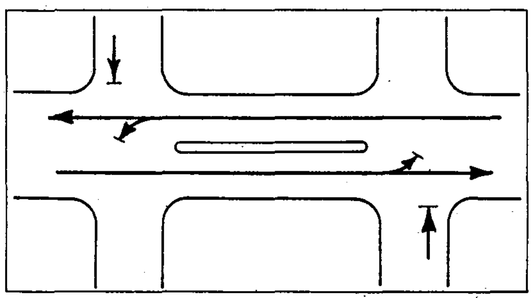


PHASE C

SEQUENCE I



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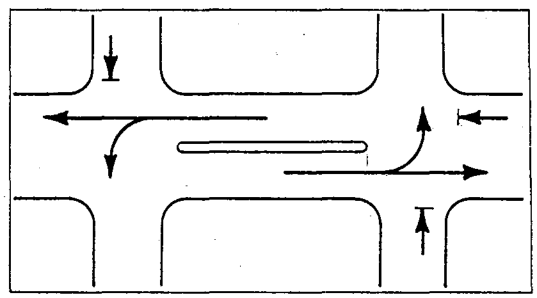

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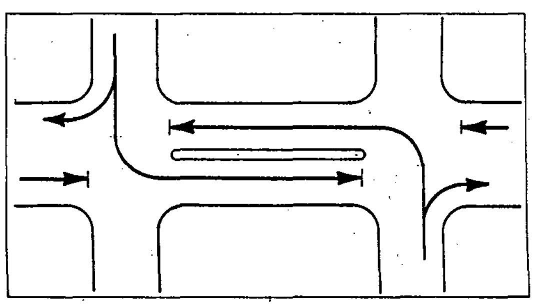


PHASE C

SEQUENCE II

SIGNAL PHASINGS

FIGURE 2

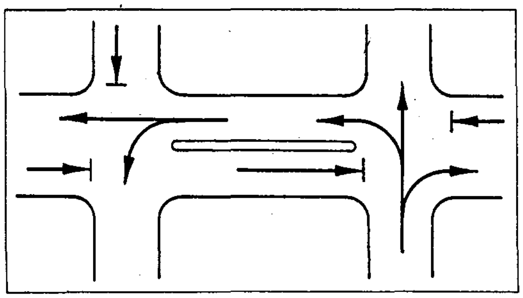
Signal Phasing

Figure 2 indicates two possible phasing arrangements for diamond interchange signalization. Although these phasing arrangements represent only two of numerous sequences which are possible, they illustrate the problems incurred in developing signal phasings for diamond interchanges.

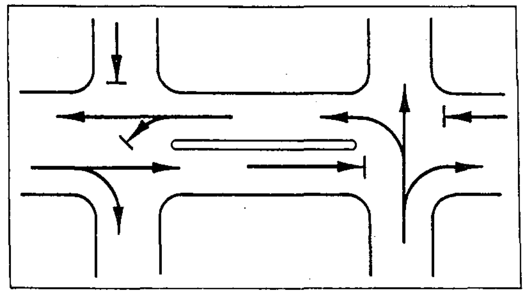
In Sequence I (Figure 2) clearance phases must be added following the A and B phases to clear the interior approaches for storage of the frontage road movement on phase C. This in effect creates a four-phase cycle (if the two clearance intervals are considered approximately equal to one phase) with a 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 upon 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.

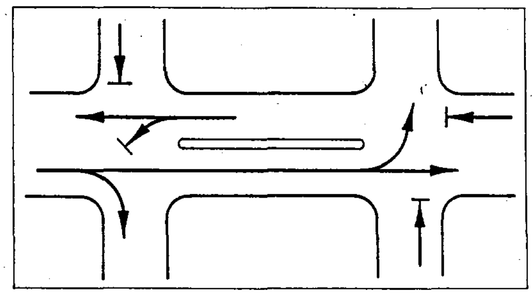
Sequence II allows the interior approaches to clear on phase B and gives preference to moving major street traffic. However, a serious left-turn storage problem is often created by this sequence. Left turns from both of the major street approaches are stored during phase A, and it must be considered that an average diamond interchange can store only a maximum of seven 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.



PHASE A



PHASE A OVERLAP



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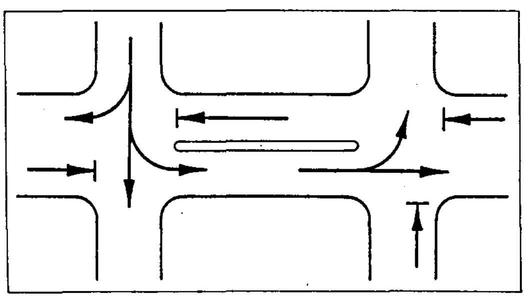
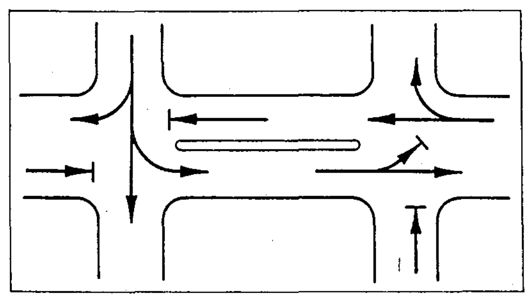
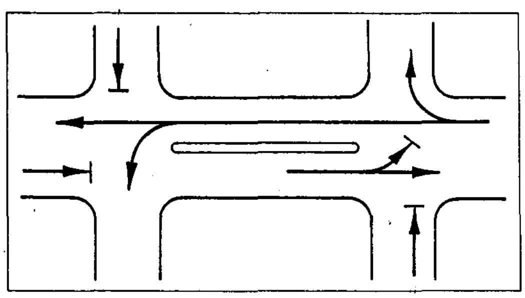


PHASE C



PHASE C OVERLAP



PHASE D

RECOMMENDED SIGNAL PHASING FOR CONVENTIONAL-TYPE DIAMOND INTERCHANGE

FIGURE 3

Recommended Phasing

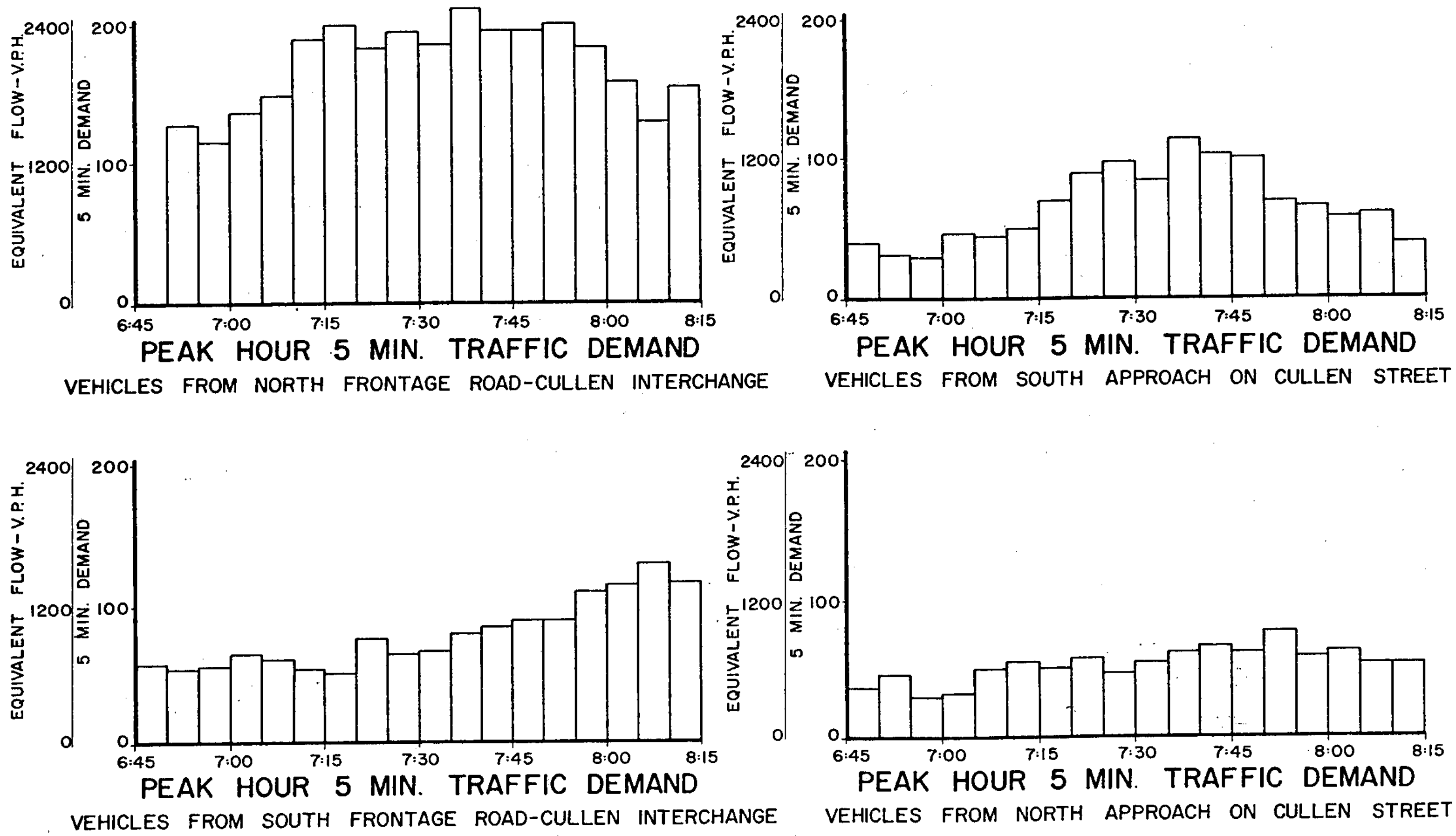
Other three-phase arrangements such as Sequences I and II yield the same basic problems of inadequate storage and sluggish, inefficient operation. Consideration of these facts and the requirements of diamond interchange signalization led to the conclusion that the four-phase sequence shown in Figure 3 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 (Figure 3).

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. The only vehicles requiring storage are those making a U-turn movement from a frontage road during the last six to eight seconds of a frontage road phase. This seldom stores more than two 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 obtains better utilization of the green time per cycle and permits the movement of large volumes through the interchange with average cycle lengths in the range of 60 to 80 seconds.

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



DEMAND VOLUMES

CULLEN BOULEVARD INTERCHANGE

HOUSTON, TEXAS

FIGURE 4

SELECTION OF CONTROL EQUIPMENT

A significant problem encountered in connection 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 which influence the selection of equipment:

1. Volume fluctuations.
2. Equipment flexibility.
3. Co-ordination.
4. Economics.

Each of these factors deserves careful consideration and is discussed in the following material.

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 five-minute intervals at several diamond interchanges revealed significant volume variations within the peak hour. A plot of five-minute demand volumes on the four approaches of the Cullen Interchange on the Gulf Freeway in Houston, Texas, is shown in Figure 4. This plot illustrates that each of the approaches had a different peaking pattern and a wide fluctuation of five-minute 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.

This volume fluctuation emphasizes the need for equipment which 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 which 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.

Co-ordination

A third factor which should receive consideration is that of progressive movement for the through traffic on the major street. Progression of this through traffic is desirable. However, since the signal system at the interchange must operate on a multi-phase 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 per cent 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 5.

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 since these will vary by time, type of equipment, and manufacturer. However, consideration of the requirements of one system over the other and the relative costs can be made.

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

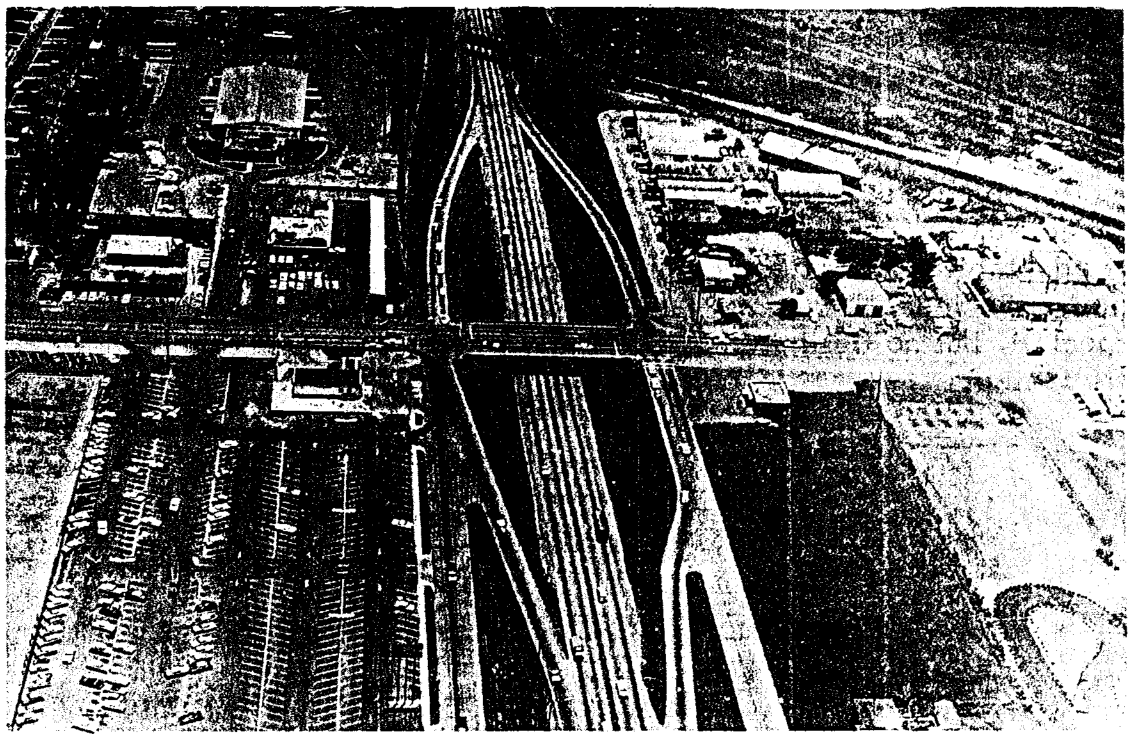
1. Additional cost of actuated control units.
2. Additional cost of the detectors (initial cost and installation) required for the actuated system.

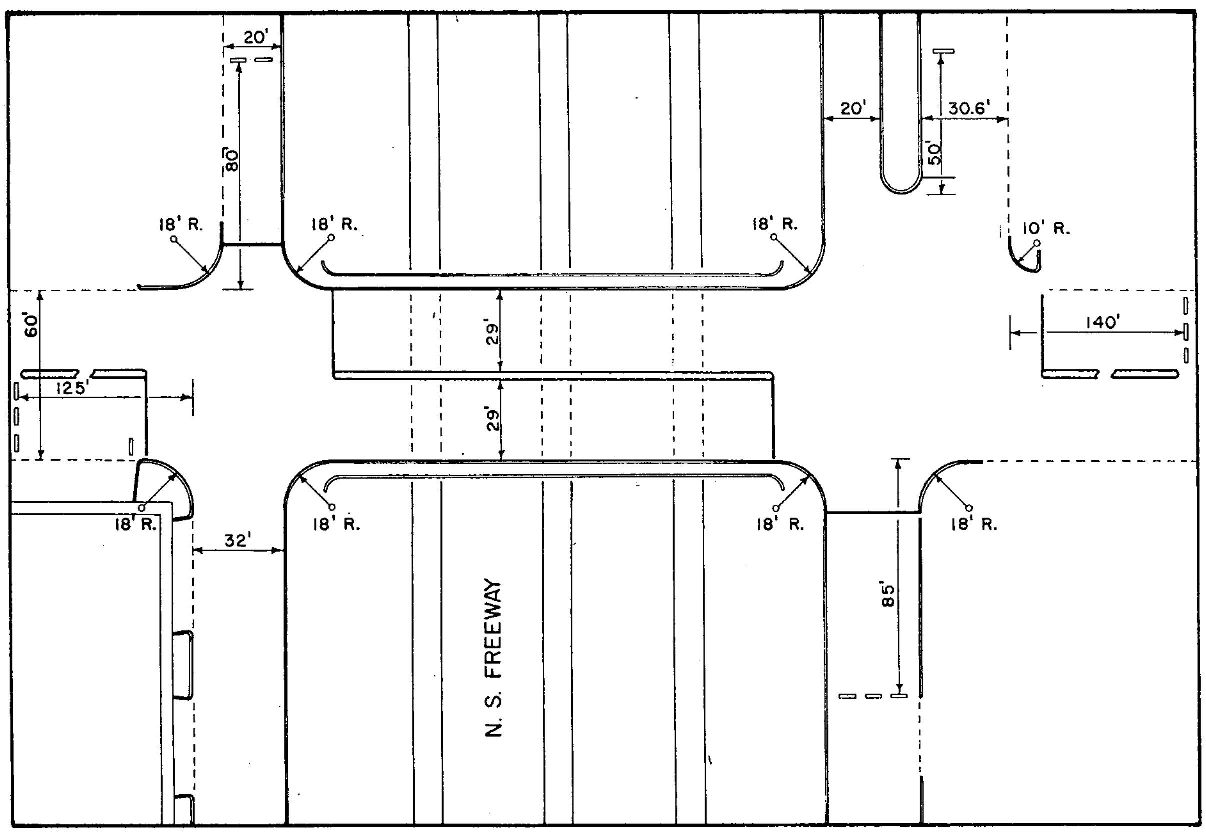
The difference in cost for the two systems (fixed-time versus traffic actuated) is a relatively small percentage of the total installation cost and loses significance when prorated over the design life of the facility.

OPERATIONAL STUDIES

Study Purpose

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 operation to be expected, but no field studies had been conducted to verify the operation anticipated.





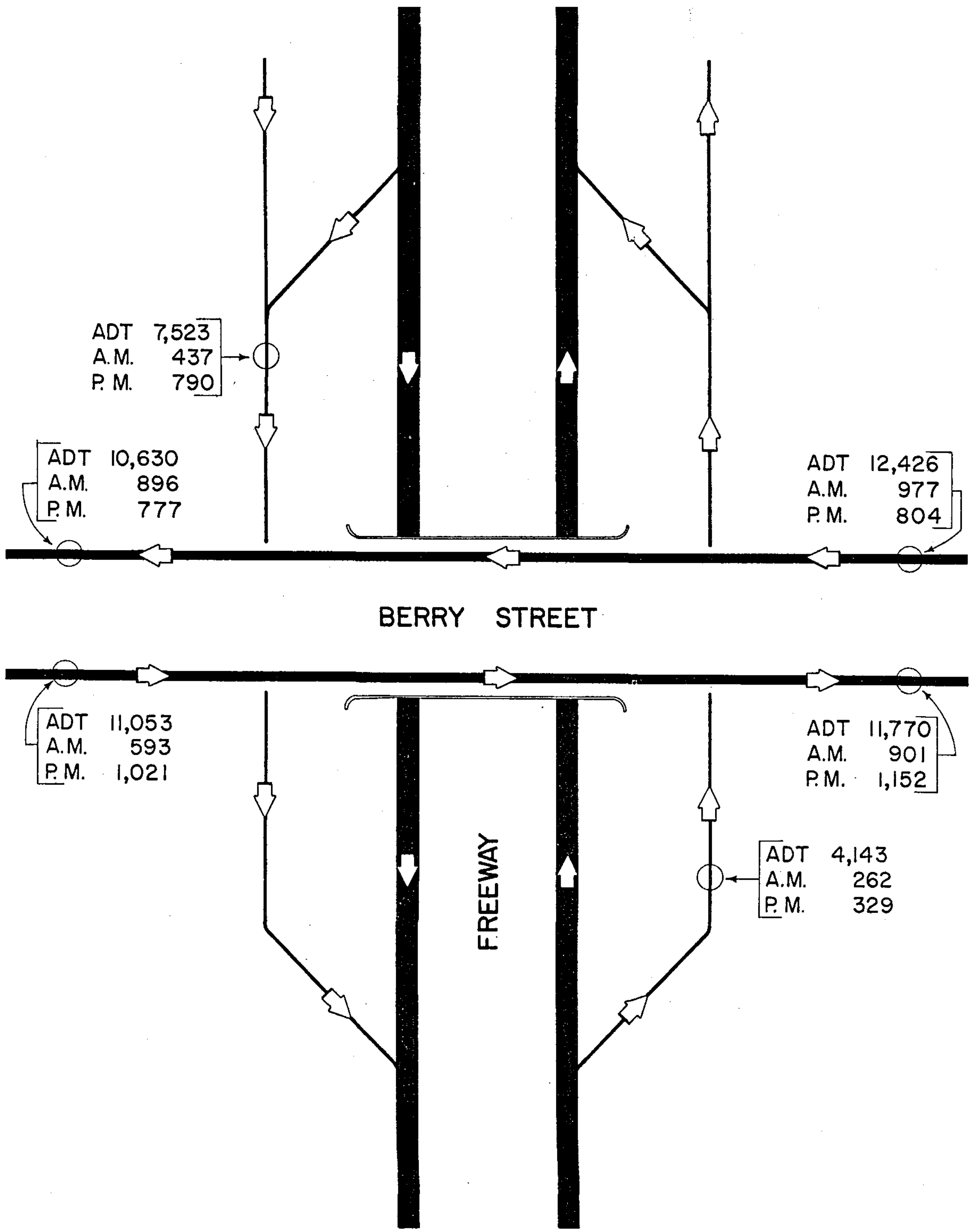
BERRY STREET INTERCHANGE
FORT WORTH, TEXAS

FIGURE 6

Study Location

The Berry Street Interchange (Figure 6) on IH 35W in Fort Worth, Texas, was selected as a study site for the operational studies. The geometrics of this interchange were essentially that of a conventional-type diamond and are representative of numerous diamond interchanges which have been constructed. Traffic volumes (Figure 7) 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.



TRAFFIC VOLUMES
BERRY STREET INTERCHANGE
FIGURE 7

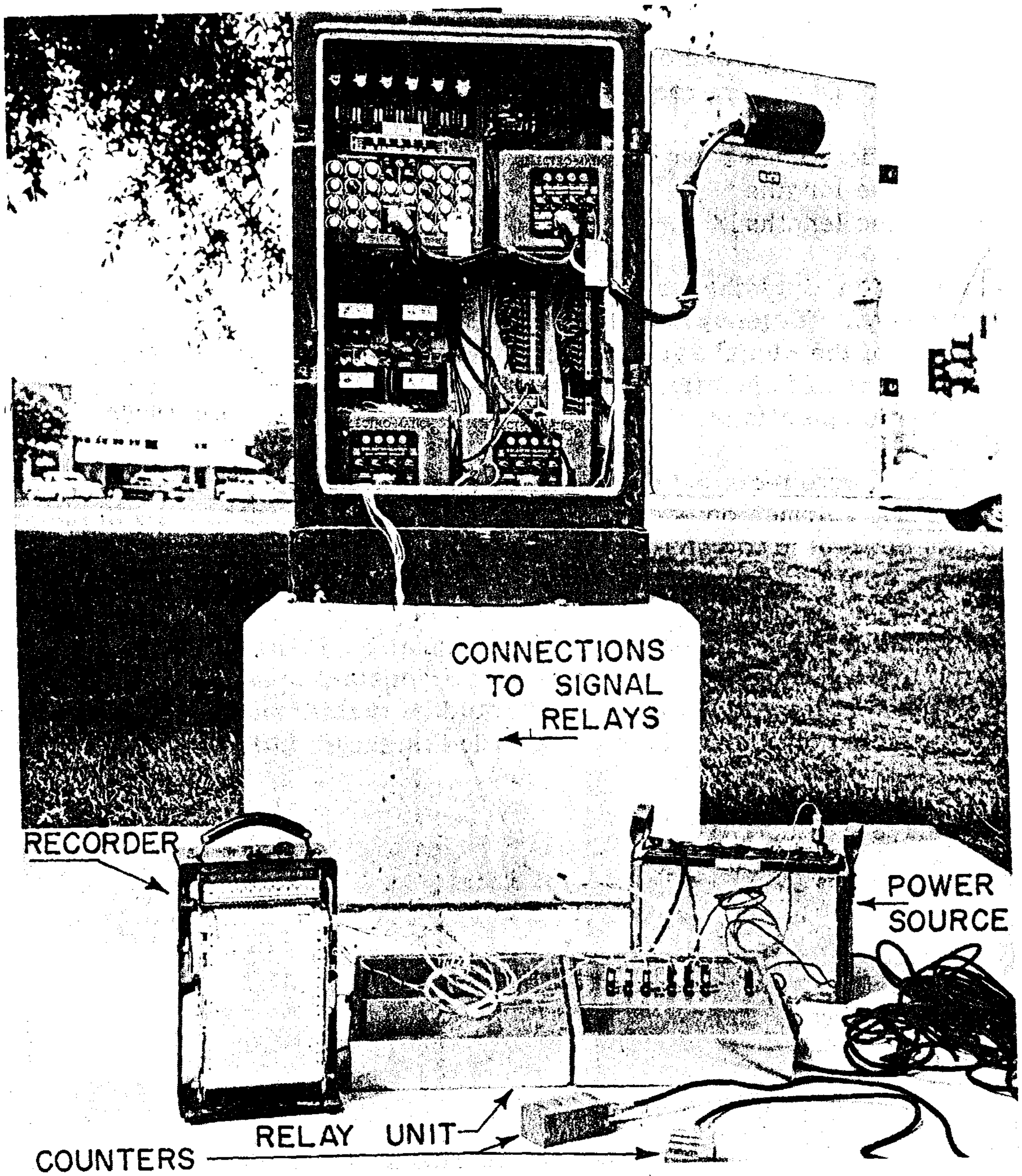
Study Procedure

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 p.m. 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.
3. Phase lengths.

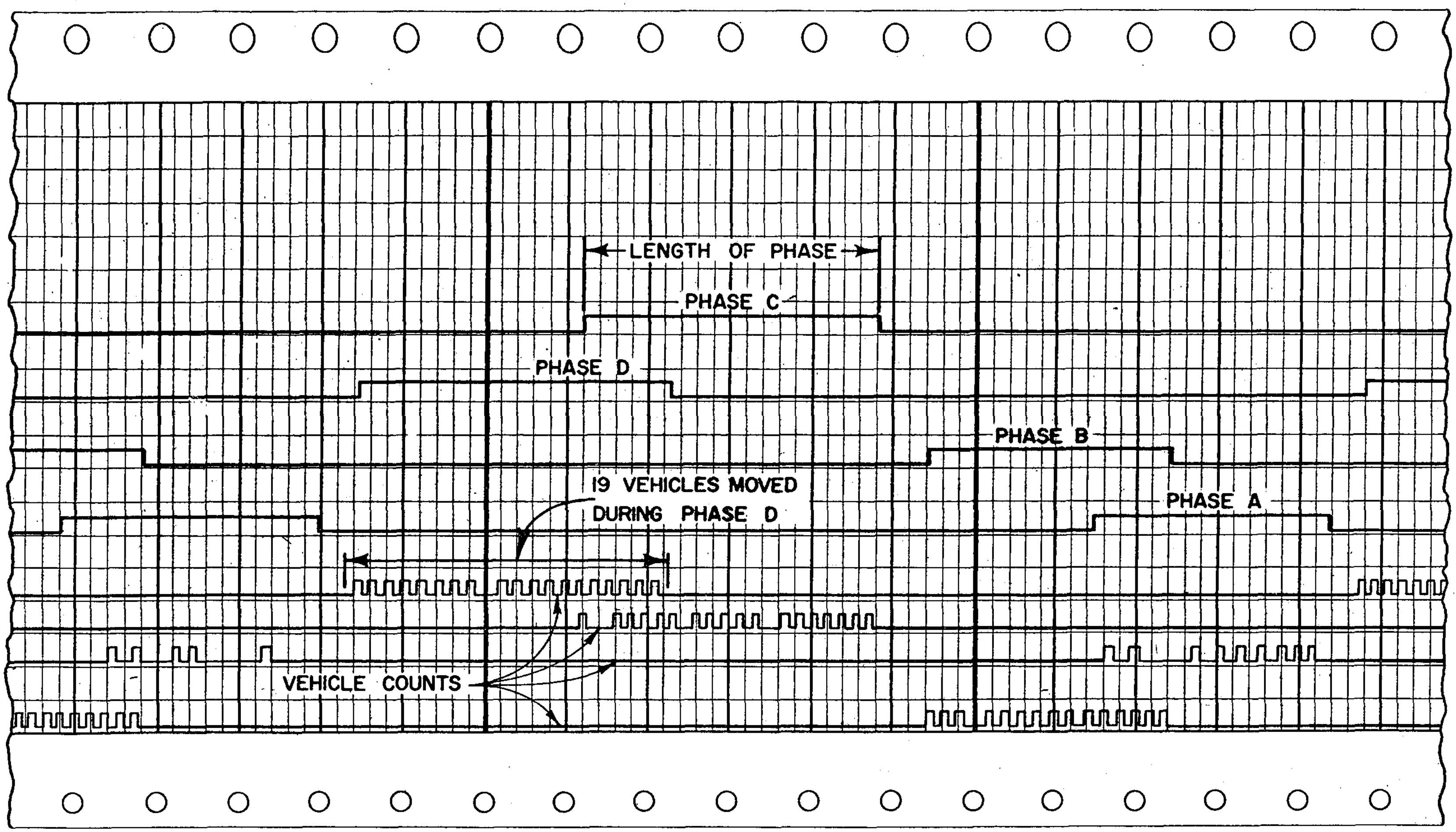
In addition, interchange operations were observed and notes were made on the general efficiency of the system. Queue lengths on the approaches, the ability of the signal system to clear the traffic demand on each cycle, and smoothness of operation were used as criteria for evaluating the efficiency of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

The data were recorded by the multi-pen recorder and equipment shown in Figure 8. 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. Since 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 9.



RECORDING EQUIPMENT

FIGURE 8



SAMPLE DATA CHART

FIGURE 9

Berry I - Three-Phase Operation

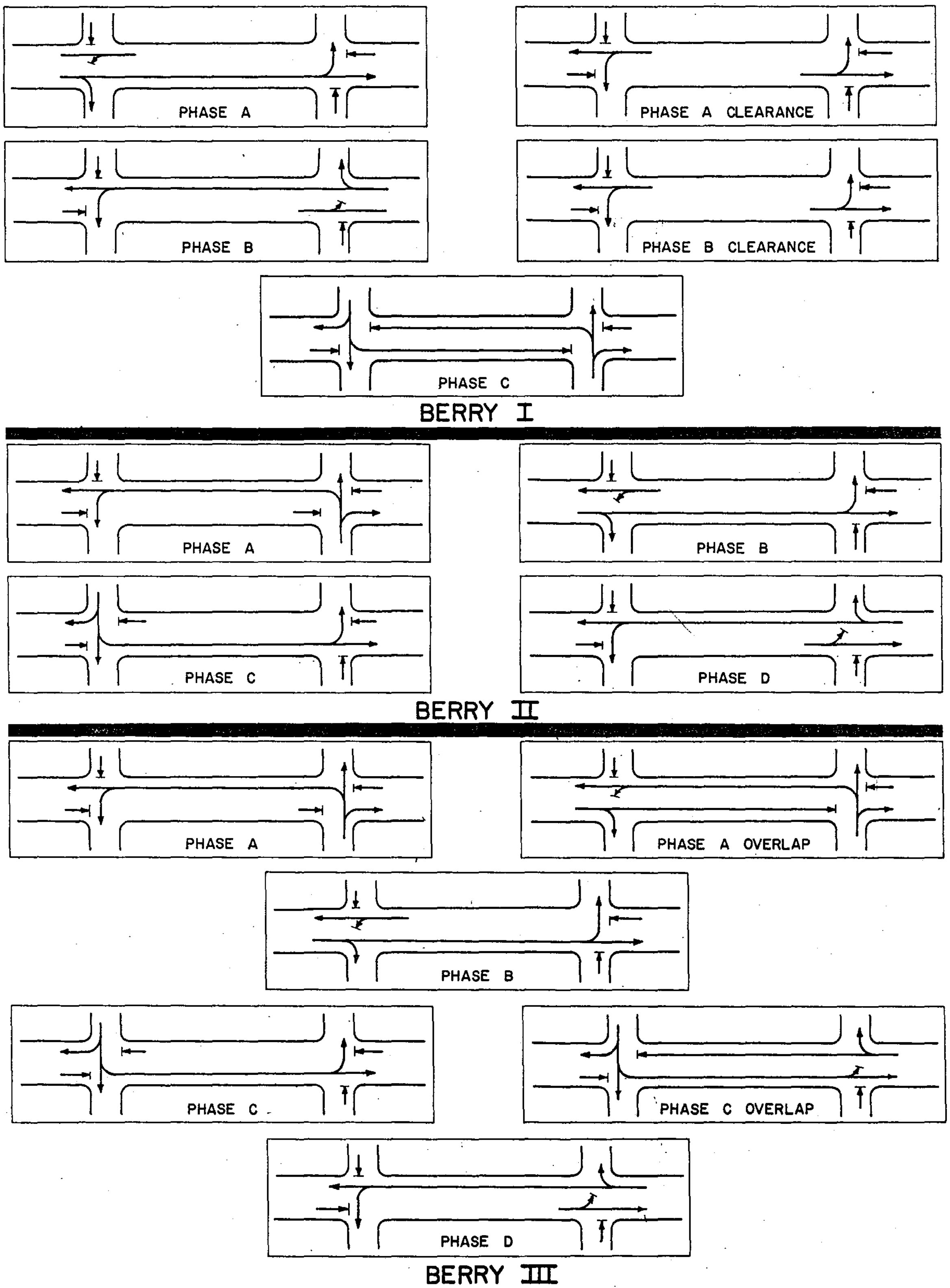
The first of a series of studies conducted at the Berry Street Interchange consisted of an evaluation of the existing actuated three-phase signal system which had been in operation for several years. The system operated with a phasing arrangement as shown in Figure 10. Dual clearance timers were used to clear the interior approaches after phase A and phase B so that the phase C movement would have adequate storage. These clearance intervals contributed to a long cycle length since they required a total of 16 seconds.

The amount of green time which 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 11 and 12 illustrate the congestion experienced during a portion of the field study. The congestion not only occurred in the intersection area as shown in Figure 11 but extended back to the exit ramps and onto the freeway (Figure 12).

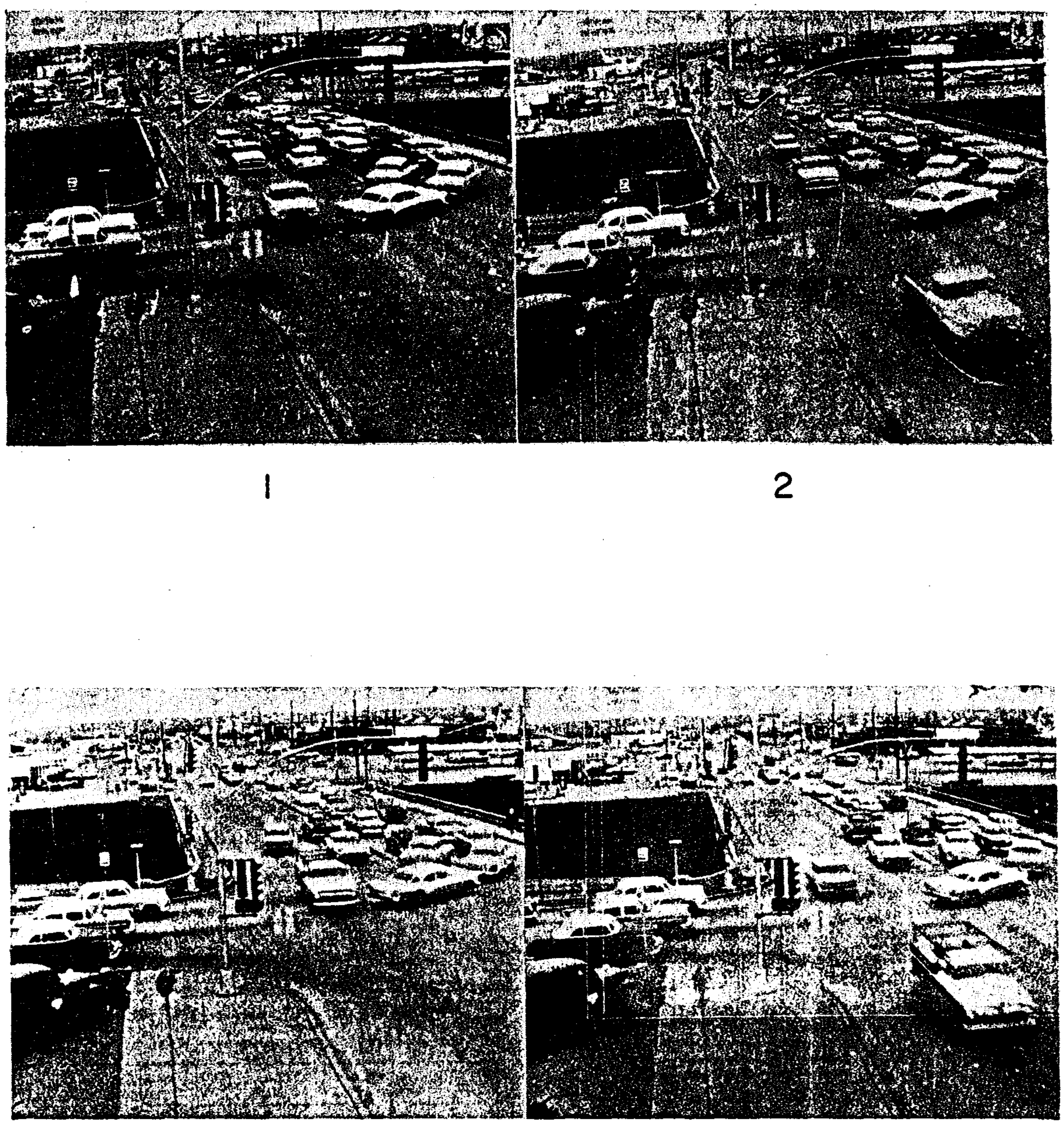
The study indicated that some of the approaches were experiencing more demand than could be accommodated. A comparison of five-minute demand volumes on the west frontage road with the number of vehicles cleared (Figure 13) indicated that the number of vehicles forced to wait at the end of each cycle was increased by small increments until a large backlog existed.

A tabulation of cycle lengths during the peak period (Table 1, appendix) showed that the cycle lengths varied from 89 to 159 seconds, with an average of 118 seconds. 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.



PHASING SEQUENCES

FIGURE 10

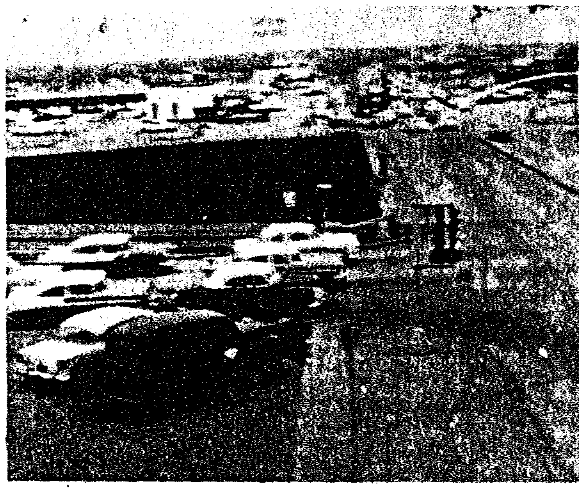


1 2

3 4

CONGESTION AT INTERSECTION

FIGURE II



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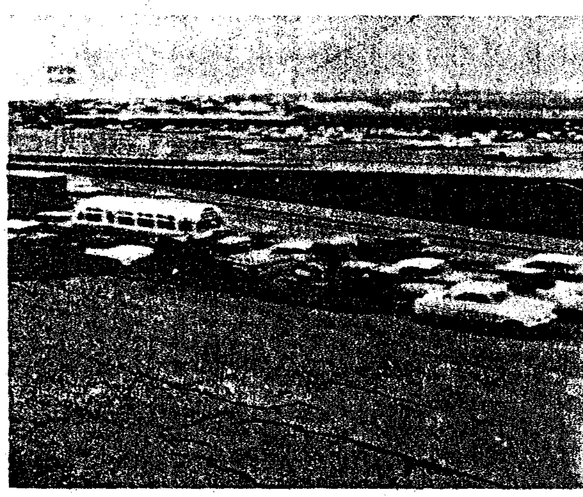
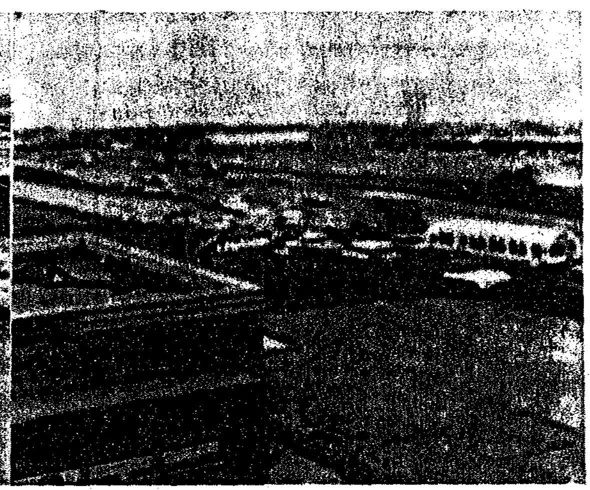
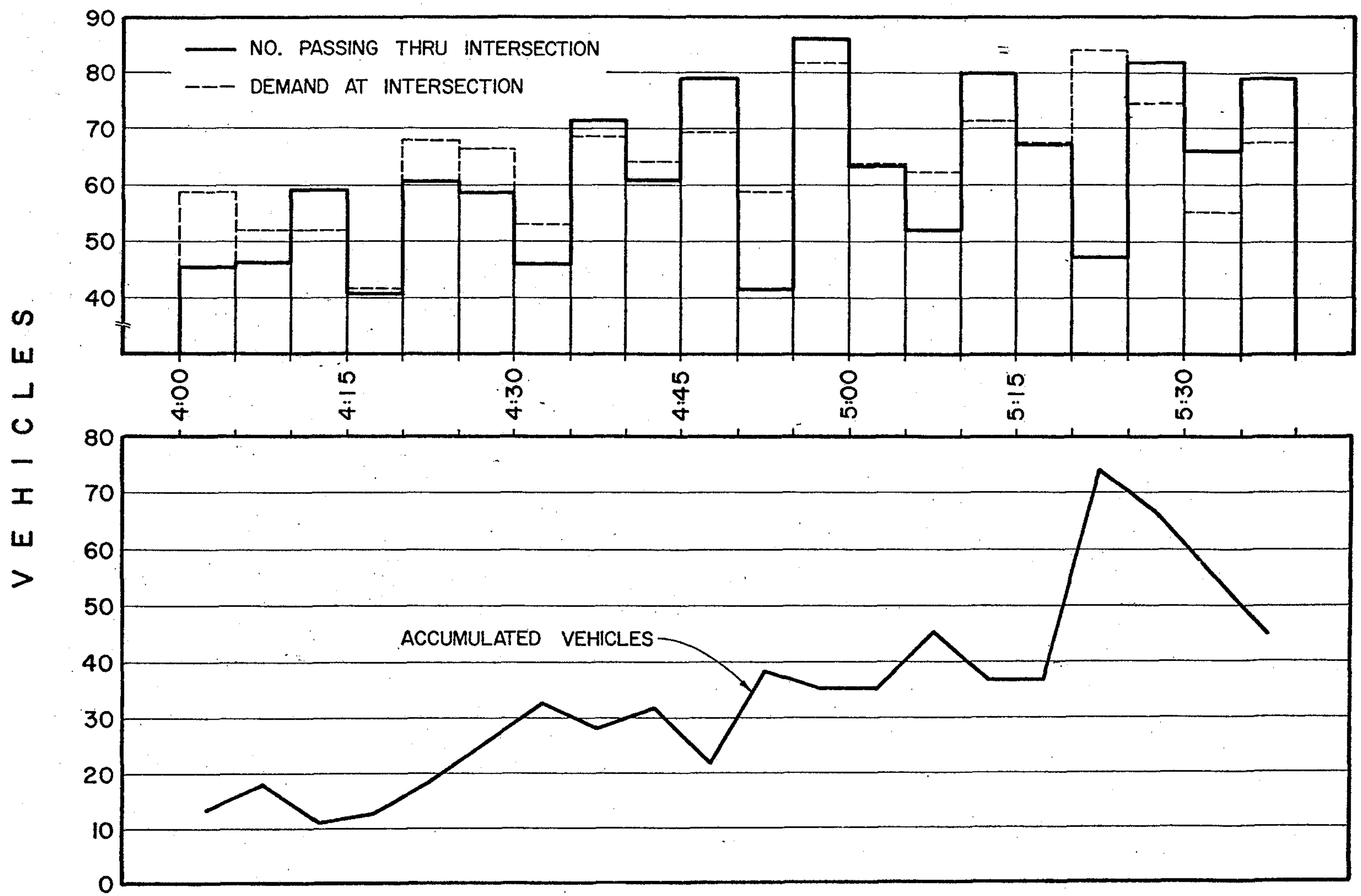




3 4

CONGESTION OF RAMP

FIGURE 12



ACCUMULATION OF TRAFFIC DEMAND

FIGURE 13

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 2-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 10.

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.

The greatest disadvantage of the four-phase system was the long cycle lengths which occurred during the peak period. Table 2 in the appendix presents a tabulation of the cycle and phase lengths recorded during the study. The cycle lengths ranged from 76 to 149 seconds with an average of 105 seconds. Although this average cycle length was considered to be excessive, it represented a 10 per cent 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 10. 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 upon 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 five seconds 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 two seconds) and provided an efficient overlap of the frontage road and major street traffic. With the two second 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 since 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 seconds with an average cycle length of 77 seconds (table 3 in appendix). This average cycle length was a 26.7 per cent reduction from that recorded in the Barry II study and a 31.6 per cent 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.) which occurred during the peak period.

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-second cycle was used with the phase lengths shown in table 4 of the appendix. 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 utilized 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 unusual condition temporarily interrupting the normal flow of traffic would have created excessive demands on all approaches. Since 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 a.m. 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. These data are shown in table 5 of the appendix. Analysis of these data plus observations made during the study indicated that satisfactory operation could be obtained during off-peak hours.

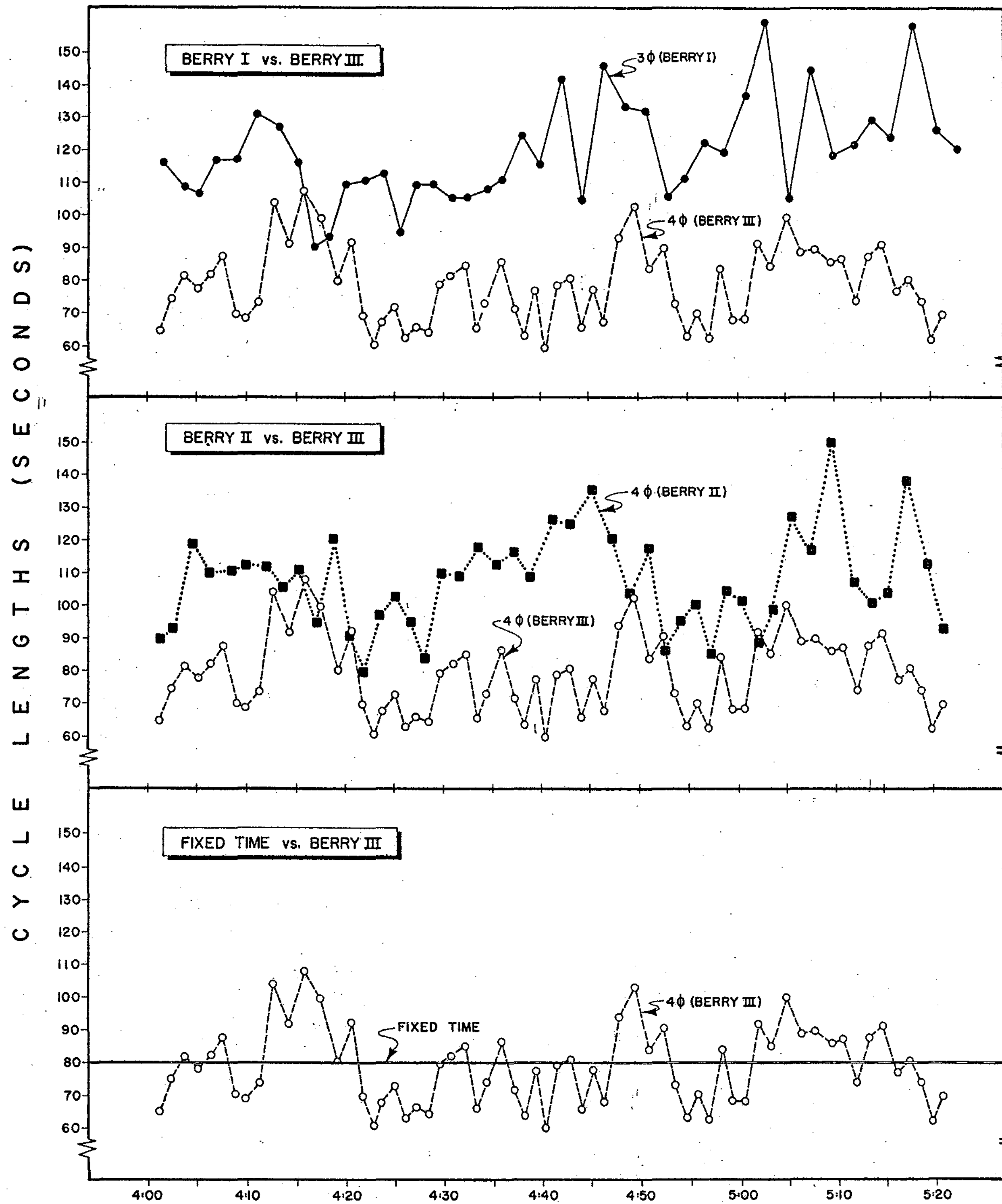
The cycle lengths recorded during this study are not indicative of the actual operation. Since there were some cycle lengths which ranged from 50 to 97 seconds, it could possibly be reasoned that inefficient operation occurred. However, the long cycles resulted from the equipment "dwelling" on a particular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

Consideration of the short cycle lengths recorded shows the efficiency that was obtained. The cycle length data indicated that 25 cycles out of 57 had a length of 40 seconds or less with a minimum cycle length of 22 seconds. 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 which had no traffic demand. The data indicated that the frontage road phases were skipped 47 times out of 114 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.



CYCLE LENGTH COMPARISONS

FIGURE 14

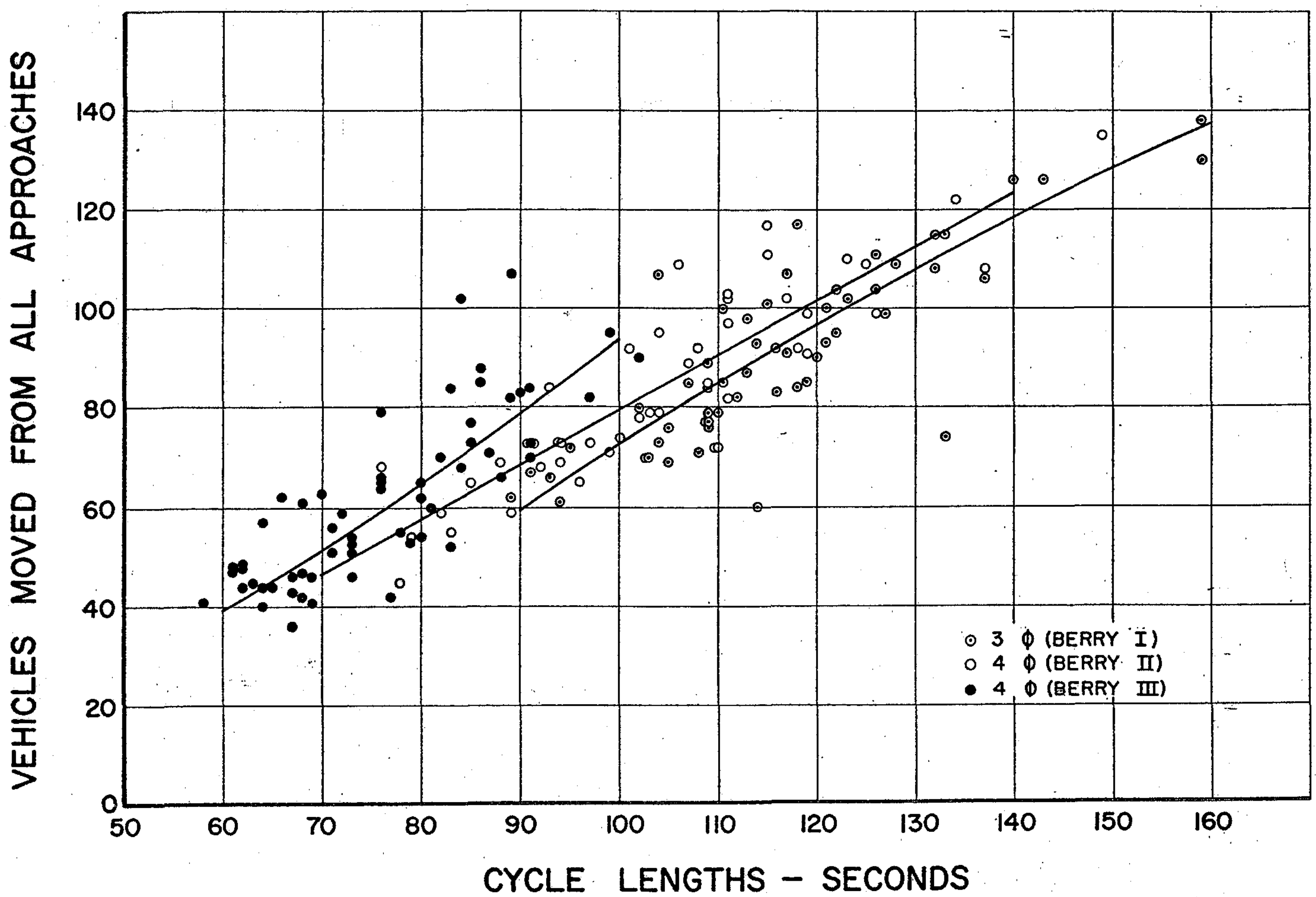
EVALUATION OF CONTROL EQUIPMENT

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 and a tabulation of the data recorded during each of the studies are presented in the appendix.

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 (Figure 14) 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 seconds and an average cycle length of 77 seconds. 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 which was 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 A. This table shows the total volume of vehicles moved through the interchange during the period 4:00 p.m. 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.



PLOT OF CYCLE LENGTHS VERSUS NUMBER OF VEHICLES MOVED

FIGURE 15

Table A

Interchange Data

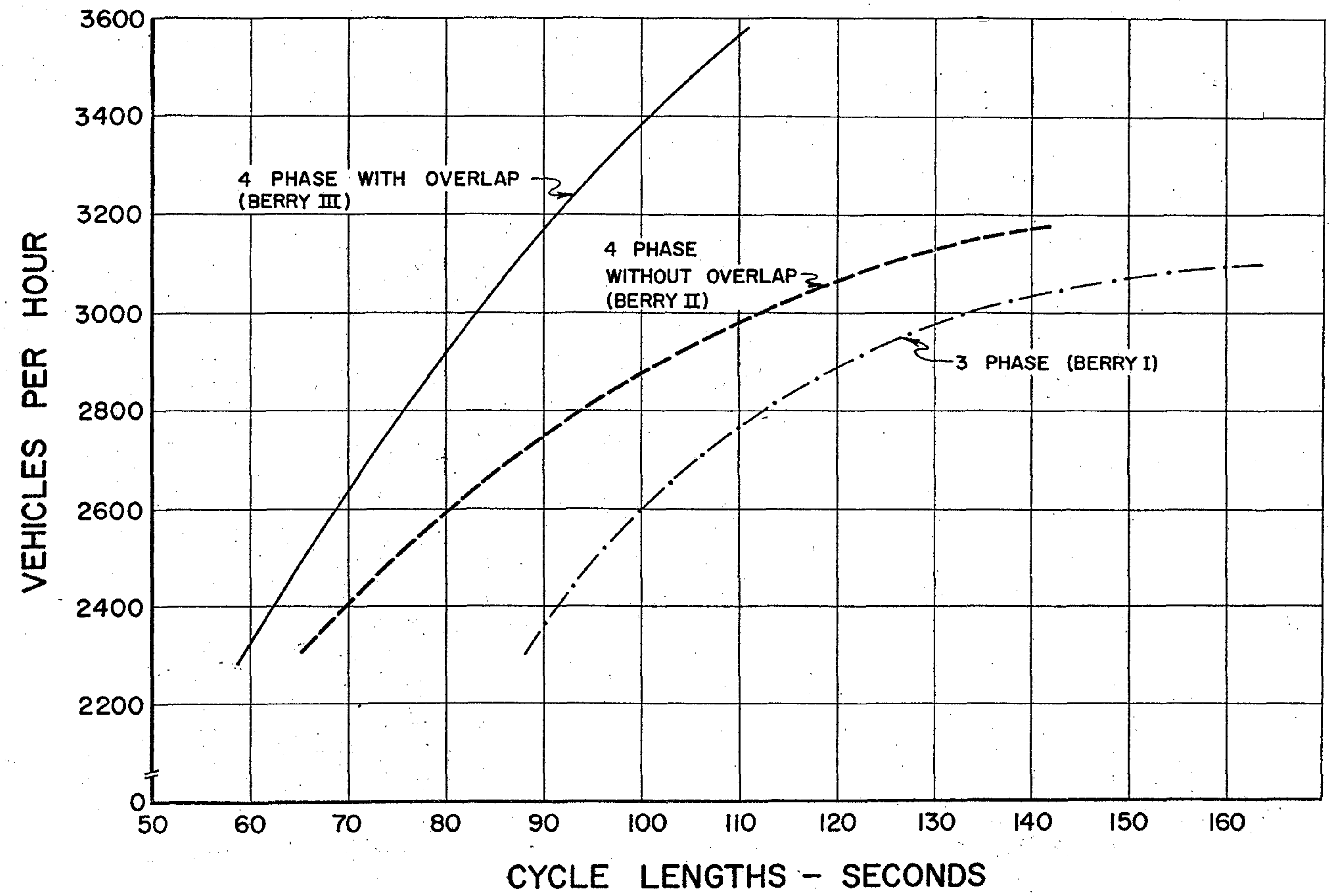
Period - 4 p.m. to 5:20 p.m.

Study	System	Average Cycle Length	Interchange Total Volume
I	3-Phase	118	3856
II	4-Phase	105	3930
III	4-Phase/Overlap	77	3825
IV	Fixed Time	80	3778

A comparison of the Berry III cycle length plot with the 80-second fixed-time cycle (Figure 14) illustrates 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-second fixed-time value.

A further indication of efficiency was given by a plot of the cycle lengths versus the number of vehicles moved on all approaches (Figure 15). 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 16). 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 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 hour were to be moved through a diamond interchange. Referring to Figure 16, the following average cycle lengths would be required:

1. 85 seconds with the Berry III sequence.
2. 115 seconds with the Berry II sequence.
3. 134 seconds with the Berry I sequence.



PLOT OF CYCLE LENGTHS VERSUS NUMBER OF VEHICLES MOVED PER HOUR

FIGURE 16

This illustrates the ability of the Berry III sequence (as compared to 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 which occurred during the Berry I study (previously illustrated) 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 hour. An actual emergency, which occurred during this study, disrupted the flow of traffic for a period of approximately five minutes 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 which utilized both fixed-time (Cullen and Way-side Interchanges - Houston, Texas) and traffic-actuated equipment (Berry Street Interchange - Fort Worth, Texas). 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:

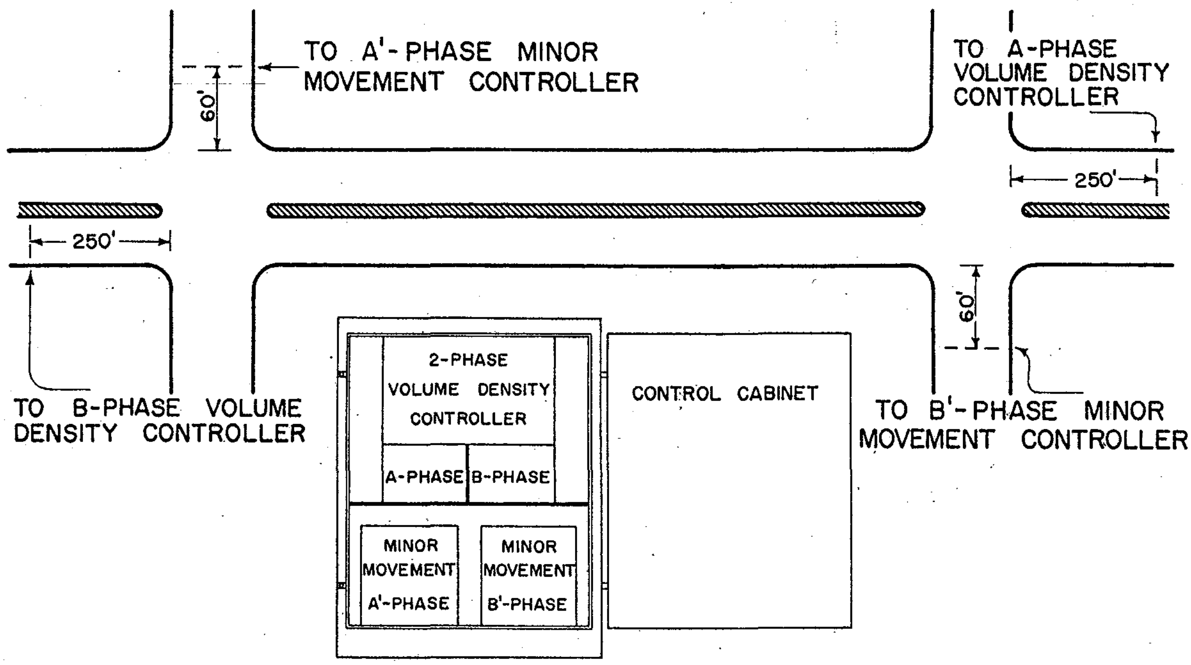
(1) The traffic studies indicated that traffic demand at diamond interchanges fluctuates widely with respect to both individual approaches and total interchange volume. This is true of peak as well as off-peak flow. It was also observed that stalled vehicles, minor accidents, or other similar disruptions 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.

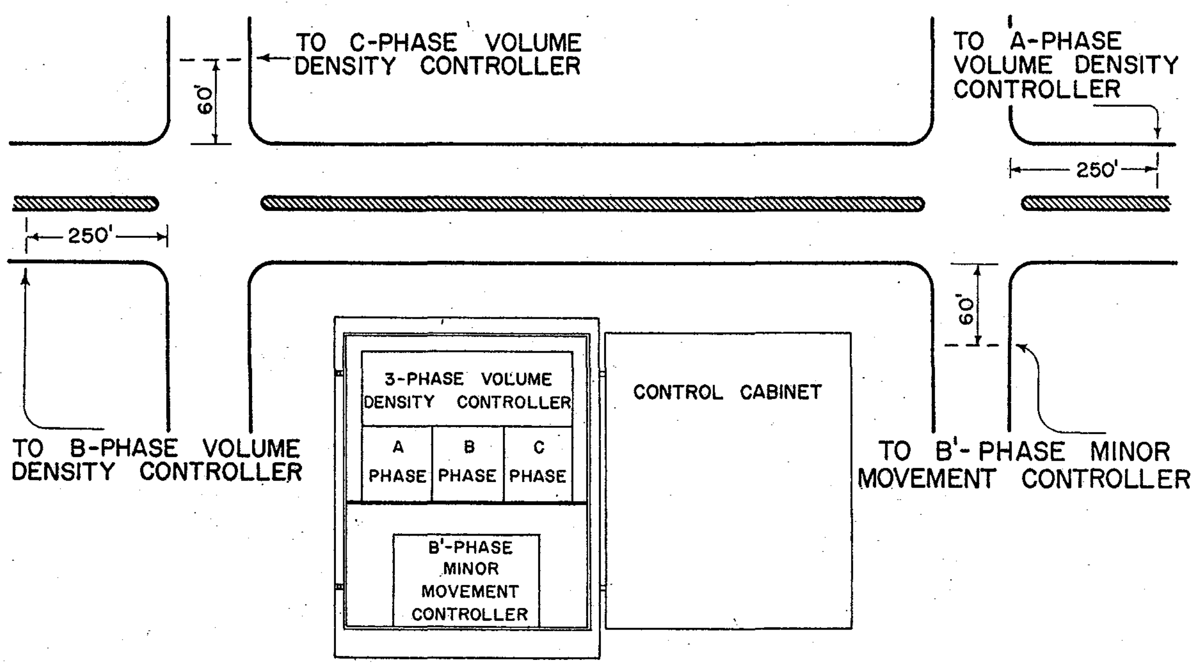
(2) In the past, some engineers have considered fixed-time control systems to be necessary at diamond interchanges in order to provide progressive movement for the through traffic on the major artery. Analyses of traffic movements at diamond interchanges showed that the major street through-movement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



SYSTEM I



SYSTEM II

BASIC CONTROL EQUIPMENT

FIGURE 17

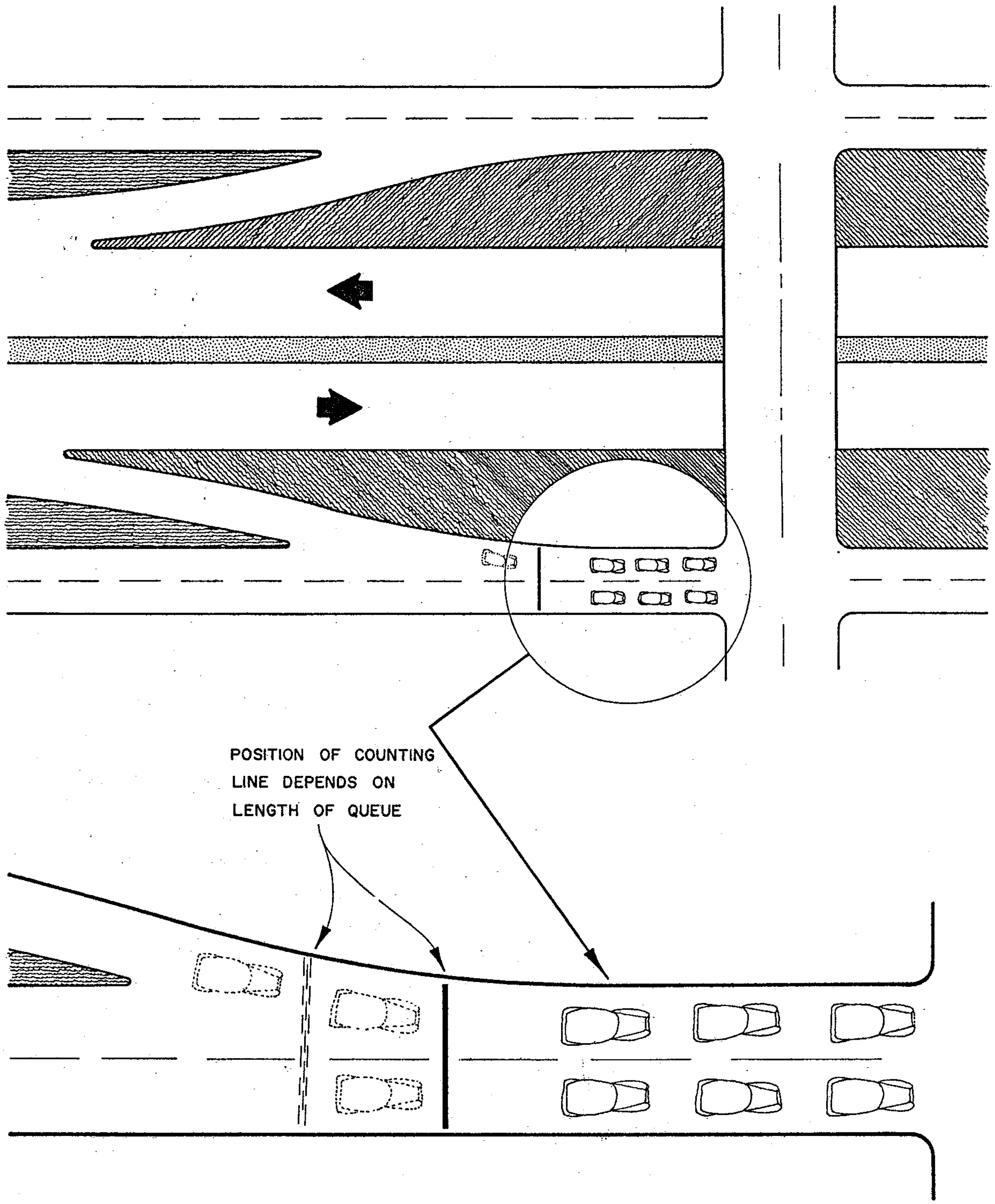
Control Equipment

Two basic traffic control systems are recommended for conventional-type diamond interchange signalization. System I (Figure 17) utilizes 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 (Figure 17) utilizes a 3-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 17. The major street detectors are placed a minimum of 250 feet back from the stop lines. This distance is required in order to obtain the advantages of the volume-density features. Detectors on the frontage roads are located at a distance of 60 feet 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 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.



PROCEDURE FOR DETERMINING TRAFFIC DEMAND

FIGURE 18

DESIGN ASPECTS OF DIAMOND INTERCHANGES

Design Volume

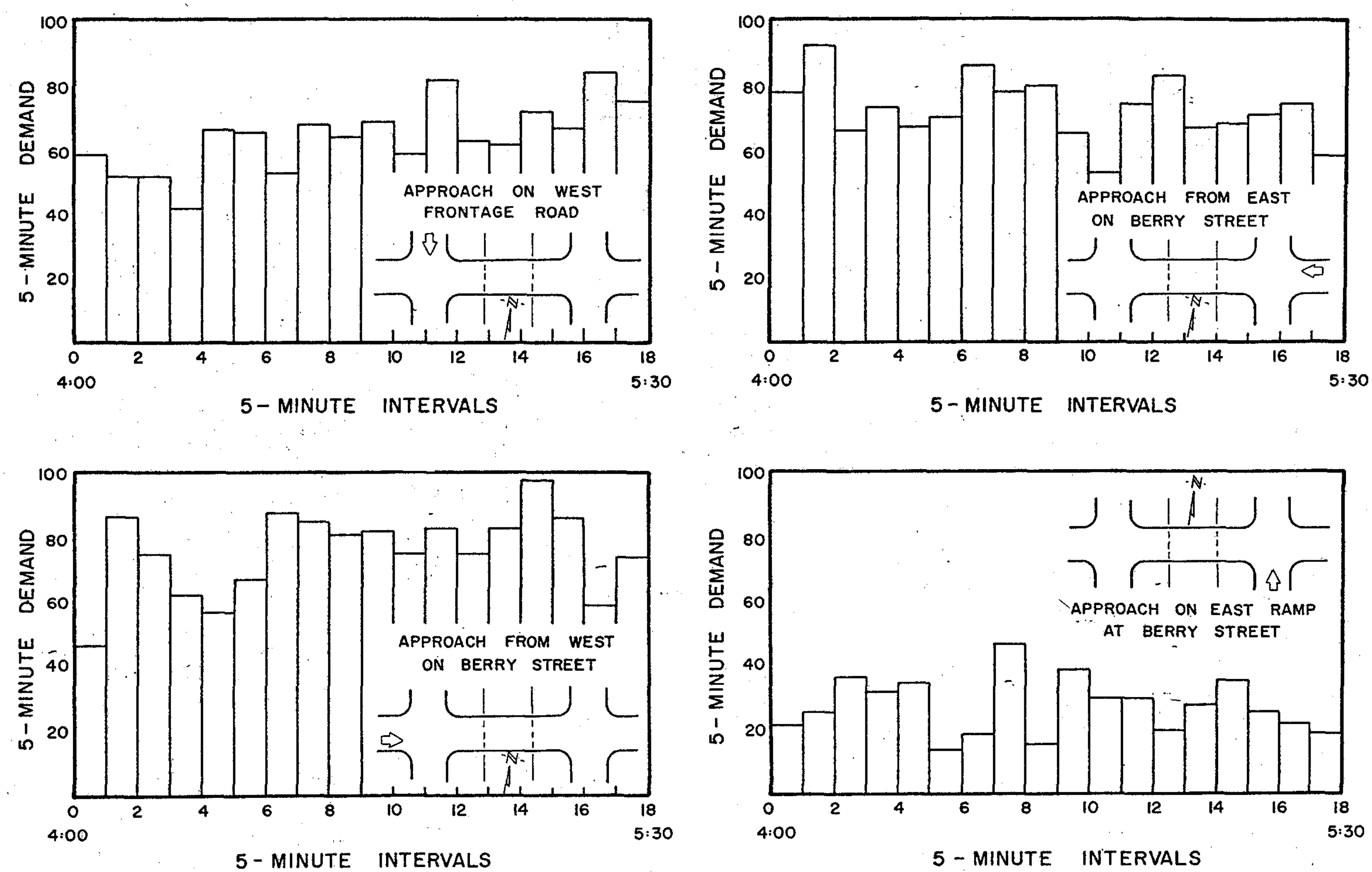
In developing the studies on diamond interchanges, it was recognized that actual traffic demand must be measured in order to determine accurately the amount of traffic that should be accommodated at a signalized intersection. This can be done by counting traffic in advance of the traffic queues on each approach as shown in Figure 18. 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. These type 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 five minute periods and by each signal cycle.

Figure 19 illustrates typical variation of traffic demand on an approach to a diamond interchange during a peak period. This fluctuation should be considered in all designs. The total hourly volume is not sufficient for design since this volume is greatly exceeded during the peak 30 minutes 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 a detailed analysis of this study is available in another report (Drew, 1961).

It was found that the average signalized intersection on a major artery in an urban area will experience a peak approximately 30 minutes in length and that 55 to 60 per cent of the total hourly demand will occur during this peak 30-minute period. On the basis of these studies, it was decided to increase all hourly volumes by a factor of 1.15 in order to obtain a proper design figure. This procedure is followed in all design examples presented in this report. Drew (1961) should be consulted for a more detailed discussion of peak-hour demand fluctuation.



DEMAND FLUCTUATIONS

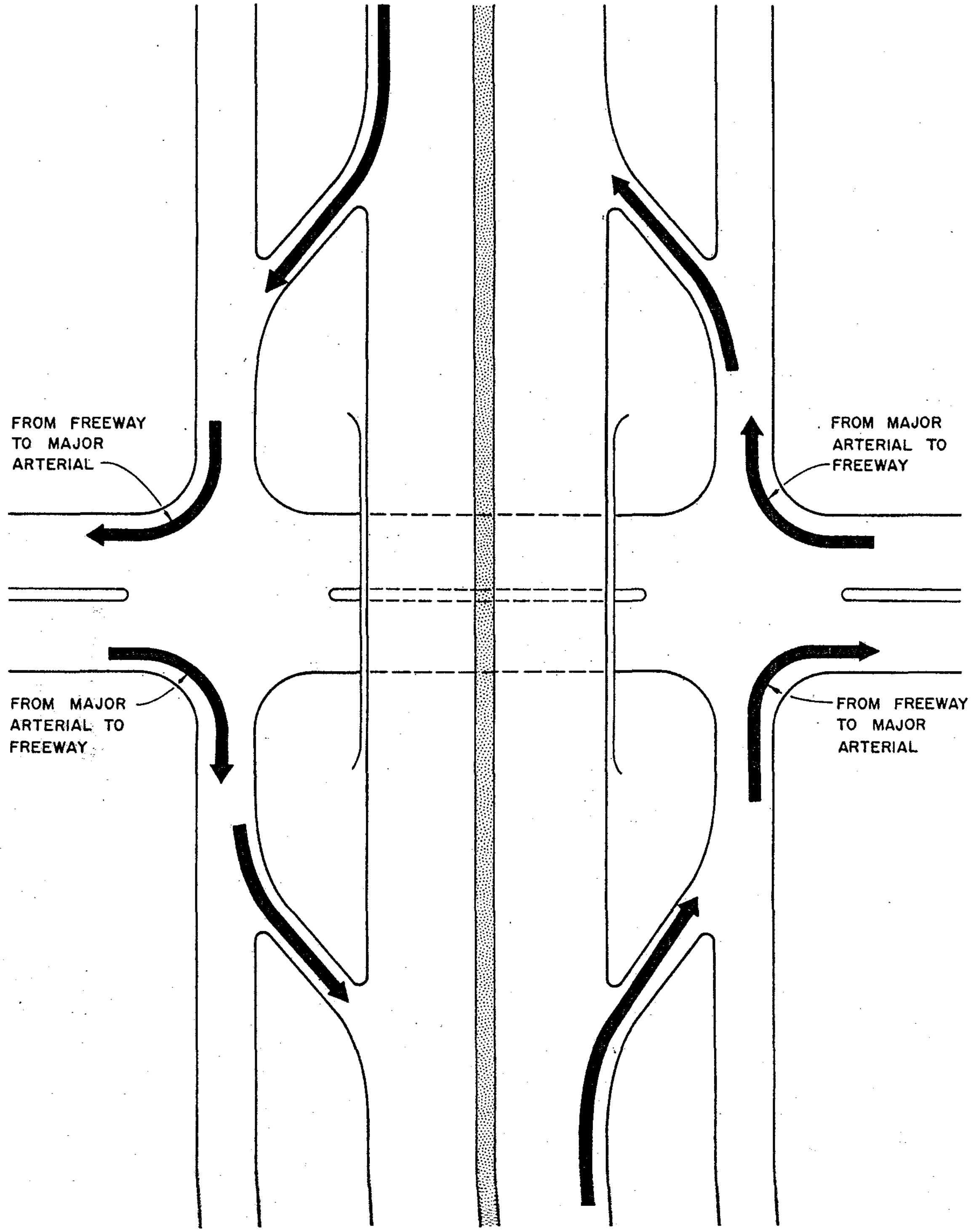
BERRY STREET INTERCHANGE
FORT WORTH, TEXAS

FIGURE 19

Lane Assignment

In working with the capacity design procedure presented in the report "Capacity Study of Signalized Diamond Interchanges," 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 since it is greatly dependent upon engineering judgment.

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



INTERCHANGE MOVEMENTS

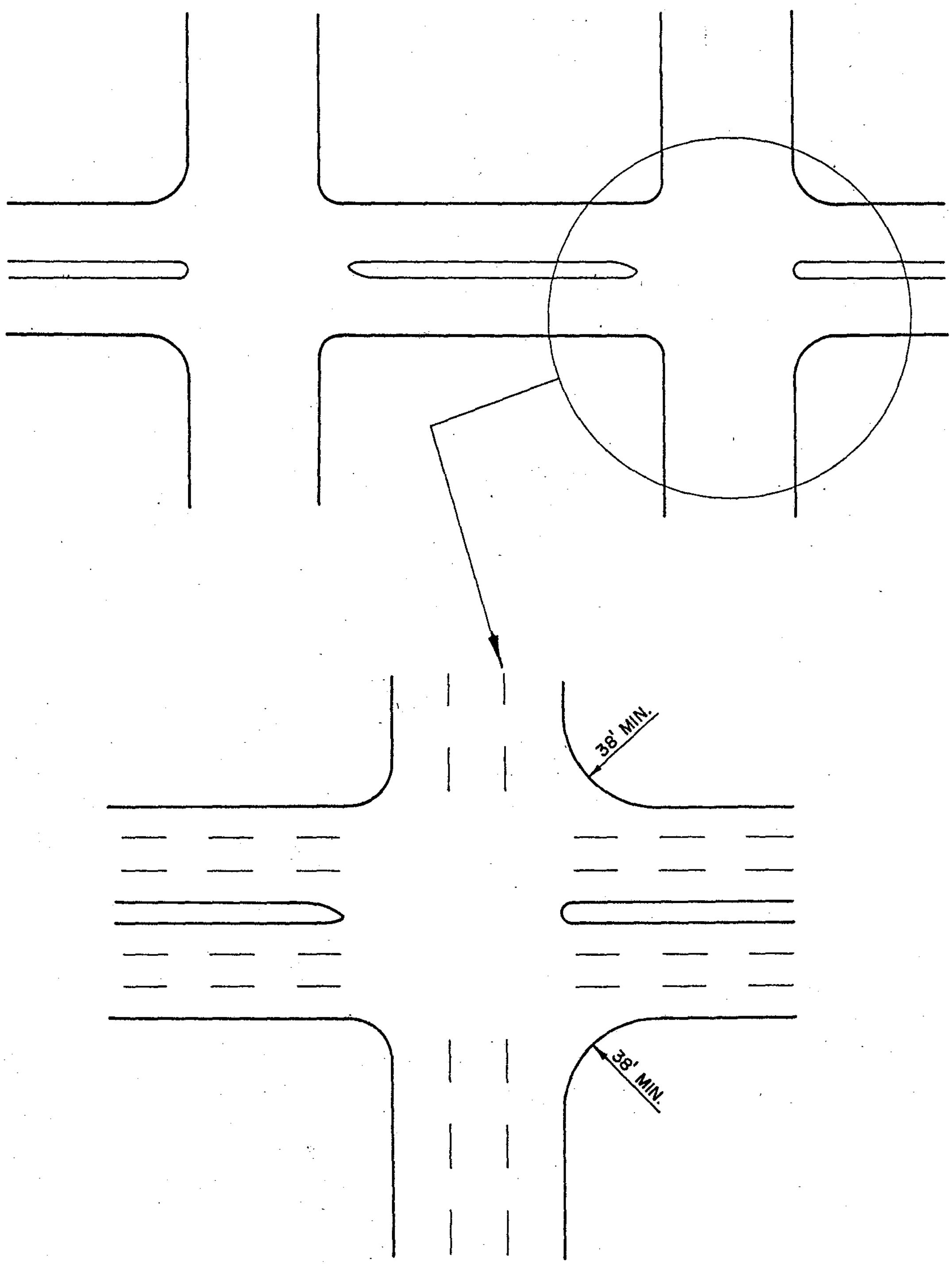
FIGURE 20

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 (Figure 20). 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 which 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 shown in Figure 21. 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.



DESIRABLE GEOMETRICS FOR RIGHT TURN MOVEMENTS AT DIAMOND INTERCHANGE

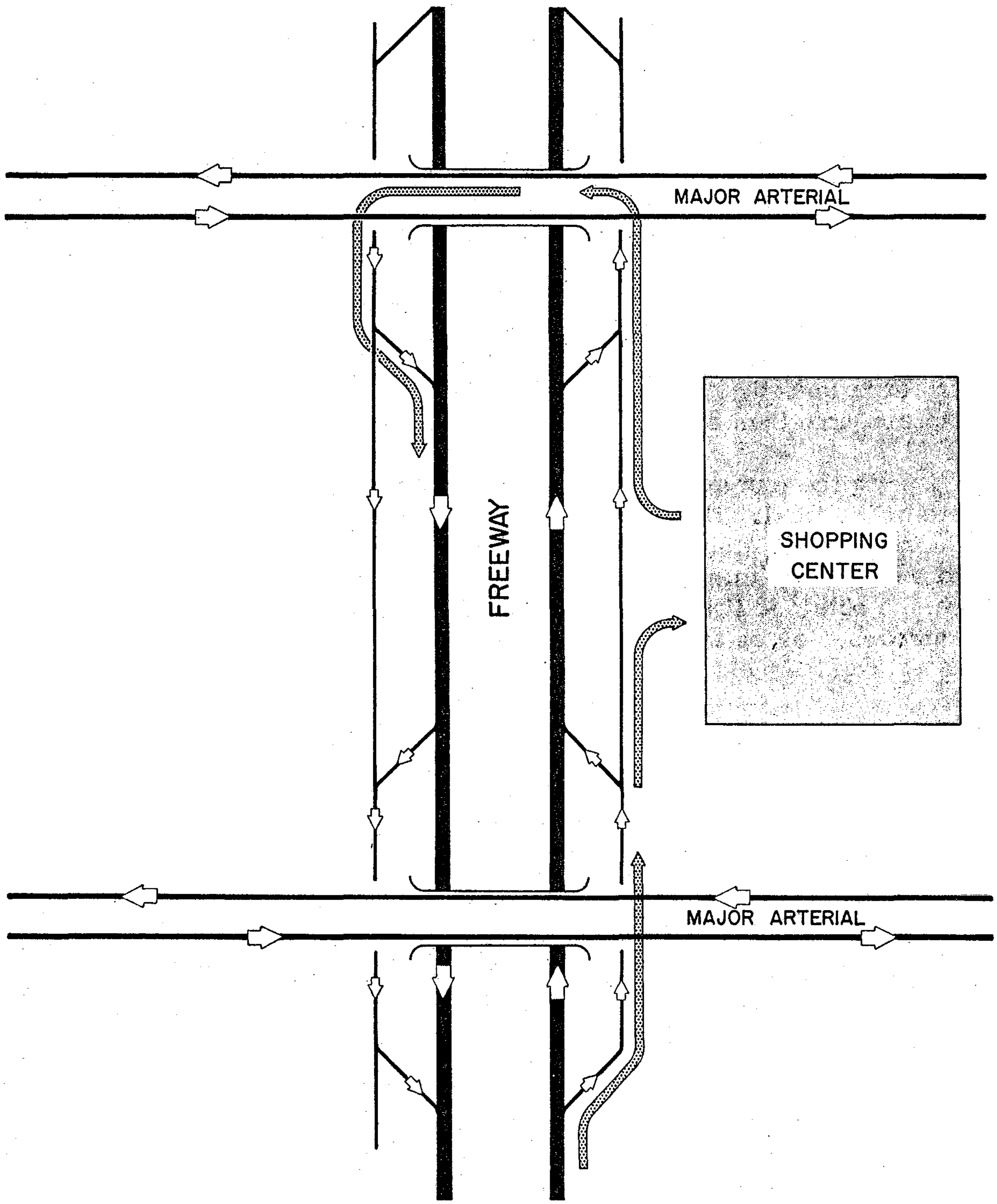
FIGURE 21

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 3 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 seven vehicles per lane.

With the four-phase operation, left turns from the interior approaches are not critical. This is true since only U-turning vehicles arriving during the last eight to ten 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.



GENERATION OF U-TURN MOVEMENTS

FIGURE 22

U-Turn Lanes

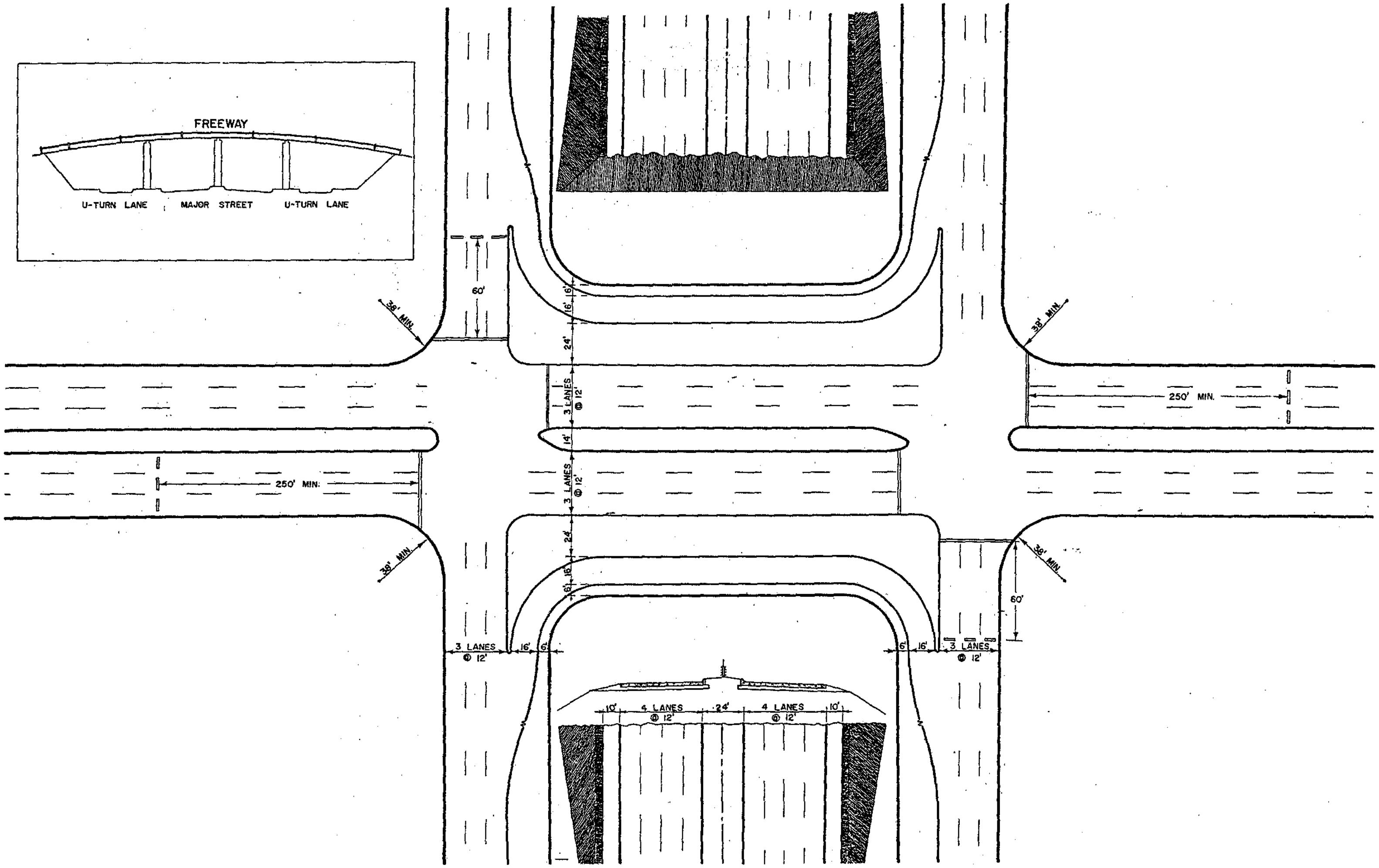
A desirable feature which can be incorporated into the design of diamond interchanges is a U-turn lane. This lane provides for the free movement of traffic from one frontage road to another. This extra lane normally requires additional structure and thus additional expense. There is a question as to 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 is dependent upon 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 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 illustrated in Figure 22. A large shopping center is being constructed adjacent to the frontage road on IH 35W in Fort Worth, Texas. 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 which will insure against the interchange becoming inadequate for the developing U-turn movements which cannot be predicted.

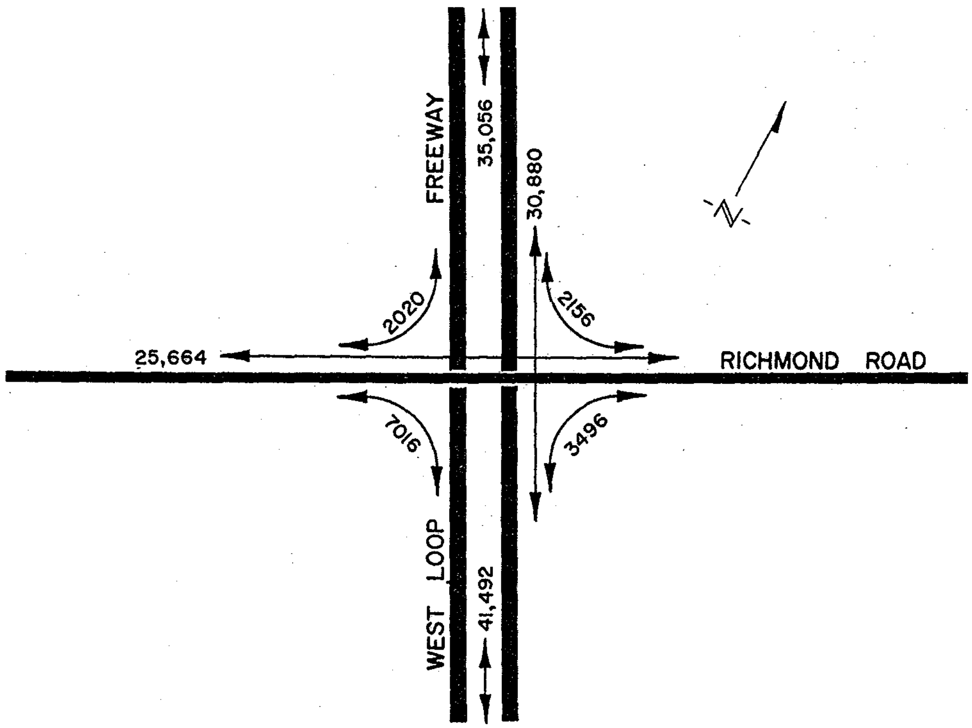


DESIRABLE GEOMETRICS FOR CONVENTIONAL-TYPE DIAMOND INTERCHANGE

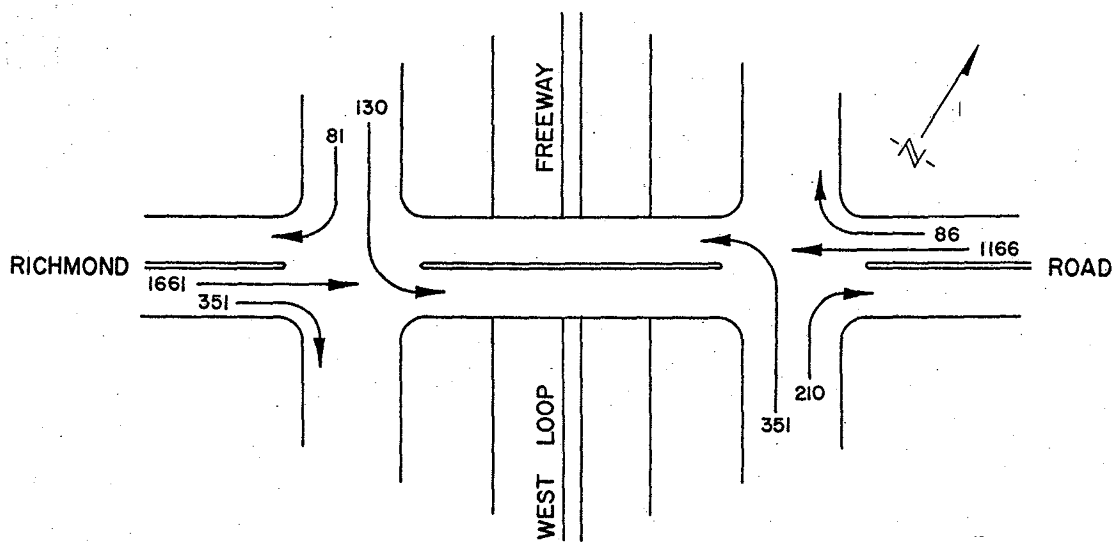
FIGURE 23

DesirableDesign

Figure 23 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 (see examples). The geometric features such as turn radii, island location, etc., are applicable to a design for any number of lanes.



ESTIMATED ADT (1980)



ESTIMATED HOURLY VOLUMES (1980)
A. M. PEAK

FIGURE 24

EXAMPLES OF DIAMOND INTERCHANGE

DESIGN AND EVALUATION

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 (Capelle and Pinnell, 1961) 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.

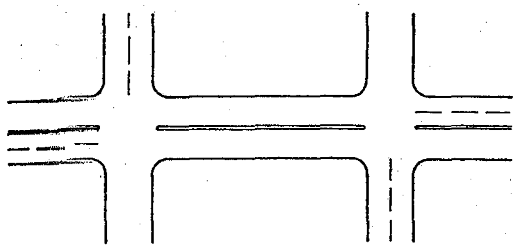
<u>Design of Future Interchanges</u>

For a design example of a future interchange, the intersection of the West Loop Freeway and Richmond Road in Houston, Texas, was considered. Future ADT volume assignments for this intersection were obtained from the Houston Urban Study and are shown in Figure 24. Assuming a K (% ADT) factor of 10 percent and a D factor (directional distribution) of 60 per cent, the interchange volumes shown in Figure 24 were developed.

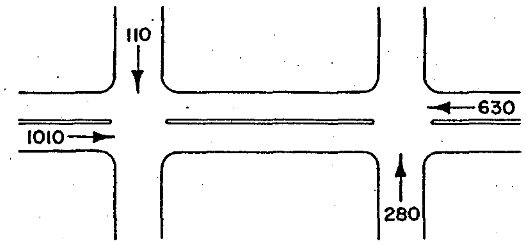
Figure 25 shows the steps necessary to evaluate and design a conventional-type diamond interchange for use at this intersection. The calculations indicated that a conventional-type diamond interchange would be adequate for this location if the required number of approach lanes and adequate signalization were provided.

It is obvious that some interchange ~~volumes~~ when subjected to this type of analysis would yield unreasonable designs. Such results would indicate a higher type directional interchange is warranted. An example of such a volume condition is shown in Figure 28. The analysis of these

STEP I – ASSUME A DESIGN BASED ON TRAFFIC MOVEMENTS SHOWN IN FIGURE 24.

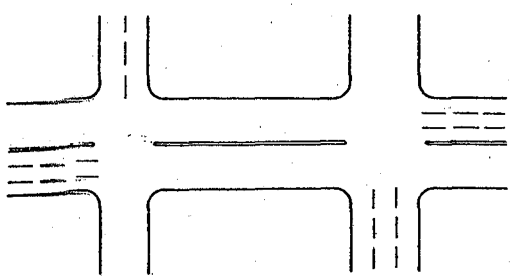


STEP II – DETERMINE CRITICAL LANE VOLUMES FOR EACH OF THE APPROACHES IN THE ASSUMED DESIGN.

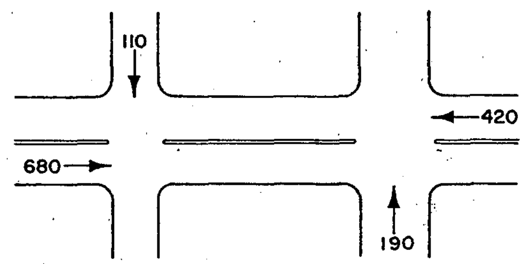


SUMMATION OF CRITICAL LANE VOLUMES
= 110 + 1010 + 630 + 280 = 2030
ADJUSTMENT FOR PEAK PERIOD: 2030 x 1.15 = 2335
COMPARE TO CRITICAL VOLUME: 2335 > 1650;
THEREFORE, THE ASSUMED DESIGN IS INADEQUATE.

STEP III – ASSUME A REVISED DESIGN TO REDUCE THE CRITICAL LANE VOLUMES



STEP IV – DETERMINE CRITICAL LANE VOLUMES FOR THE REVISED DESIGN.



SUMMATION OF CRITICAL LANE VOLUMES
= 110 + 680 + 190 + 420 = 1400
ADJUSTMENT FOR PEAK PERIOD: 1400 x 1.15 = 1610
COMPARE TO CRITICAL VOLUME: 1610 < 1650;
THEREFORE, THE REVISED DESIGN IS ADEQUATE.

SAMPLE CALCULATIONS FOR DIAMOND INTERCHANGE
WEST LOOP FREEWAY & RICHMOND ROAD
HOUSTON, TEXAS

FIGURE 25

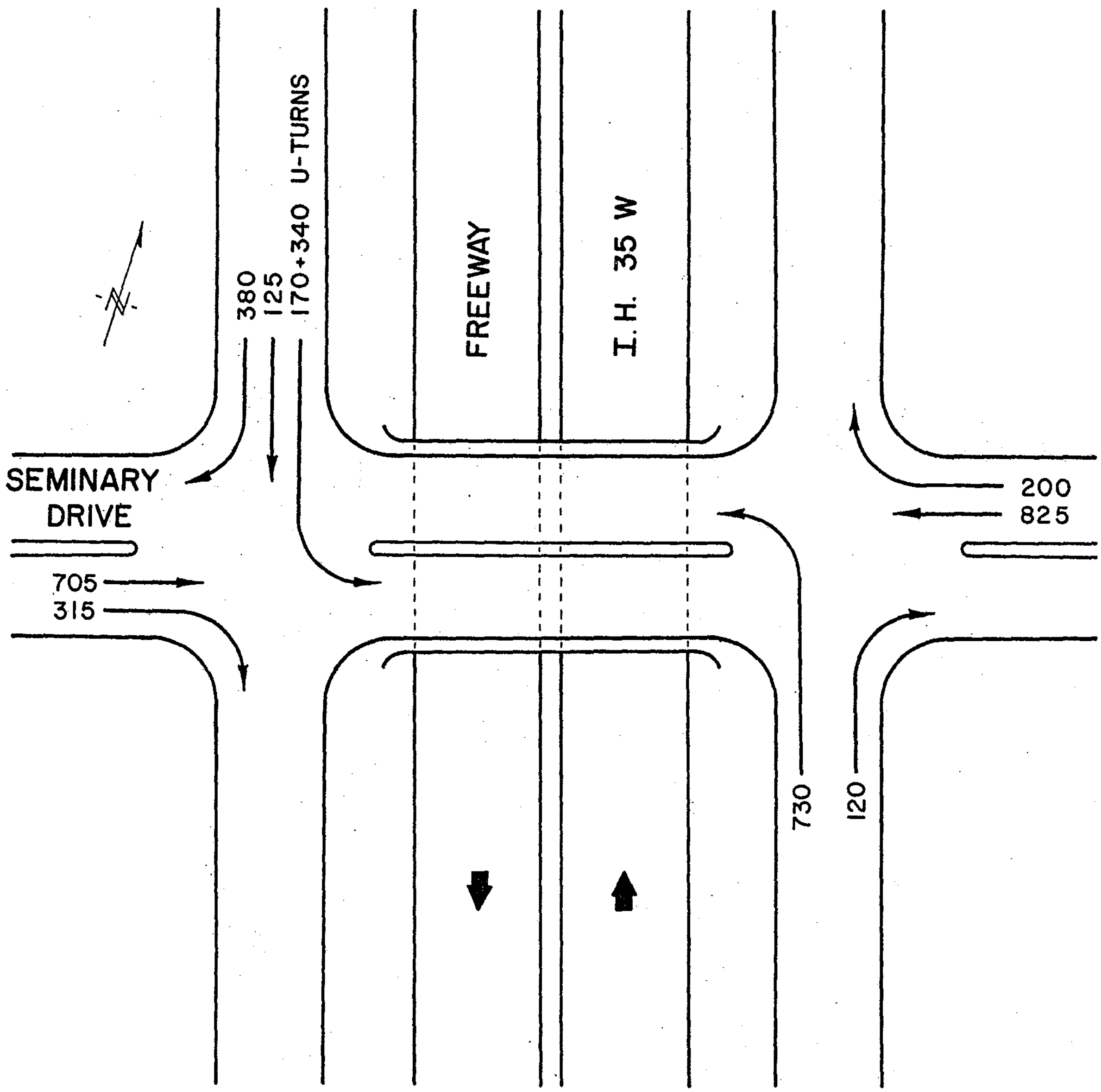
data (Figure 29) shows that a conventional-type diamond interchange would be inadequate.

Evaluation of Existing Interchanges

The evaluation of an existing interchange is illustrated by the Seminary Drive interchange on IH 35W in Fort Worth, Texas. This interchange will be greatly affected by the future construction of a shopping center near the interchange, as shown in Figure 22.

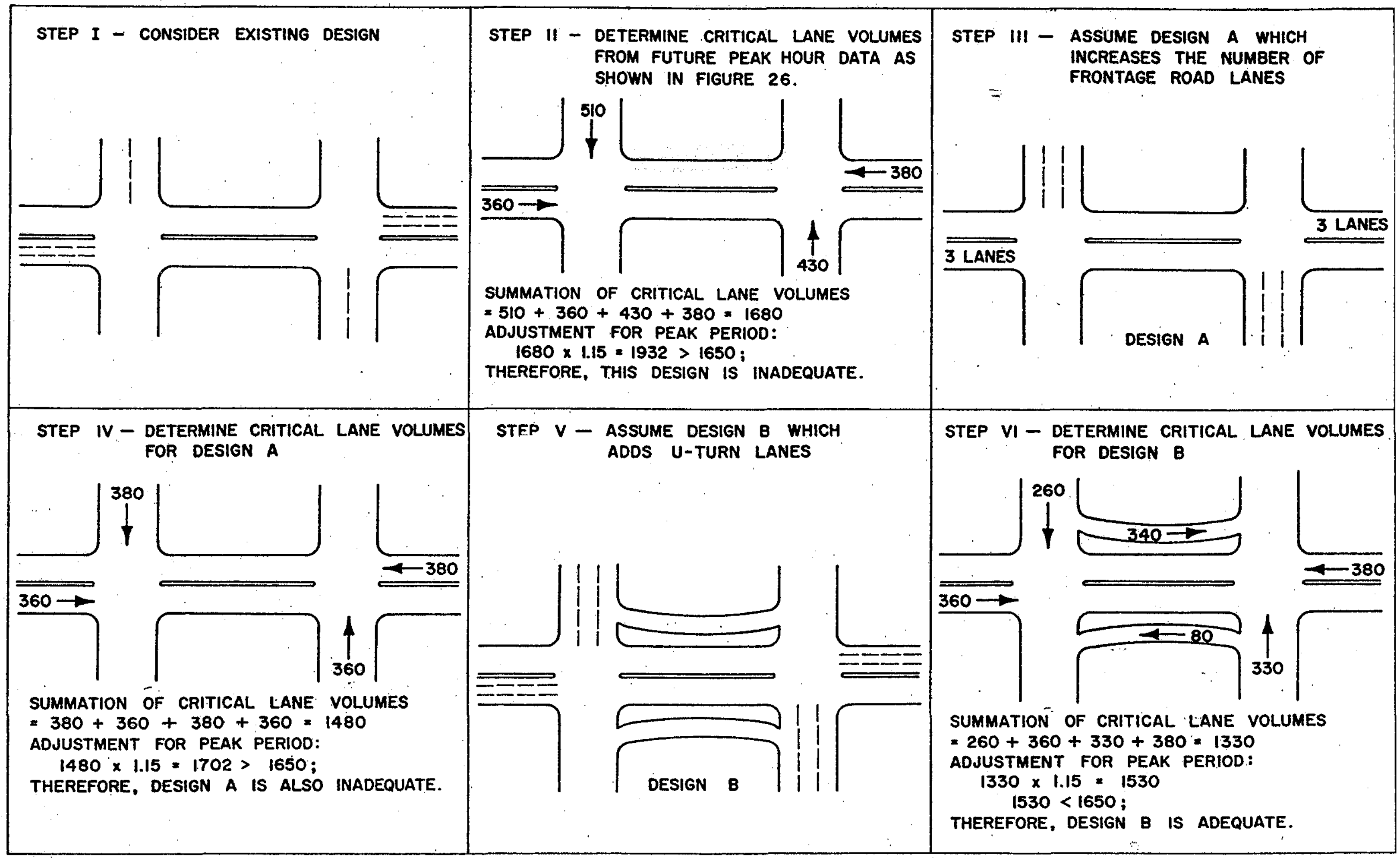
The Seminary Drive interchange is presently accommodating existing traffic volumes with little or no congestion. However, the shopping center is expected to create large U-turn movements at this interchange in the future. This is illustrated by the predicted volumes shown in Figure 26. Since there are 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 27. The modifications (indicated by this analysis) should provide the required capacity to accommodate the future traffic demand.



ESTIMATED PEAK HOUR VOLUME (1975)
(A.M. PEAK)
SEMINARY DRIVE
I.H. 35 W.
FORT WORTH, TEXAS

FIGURE 26

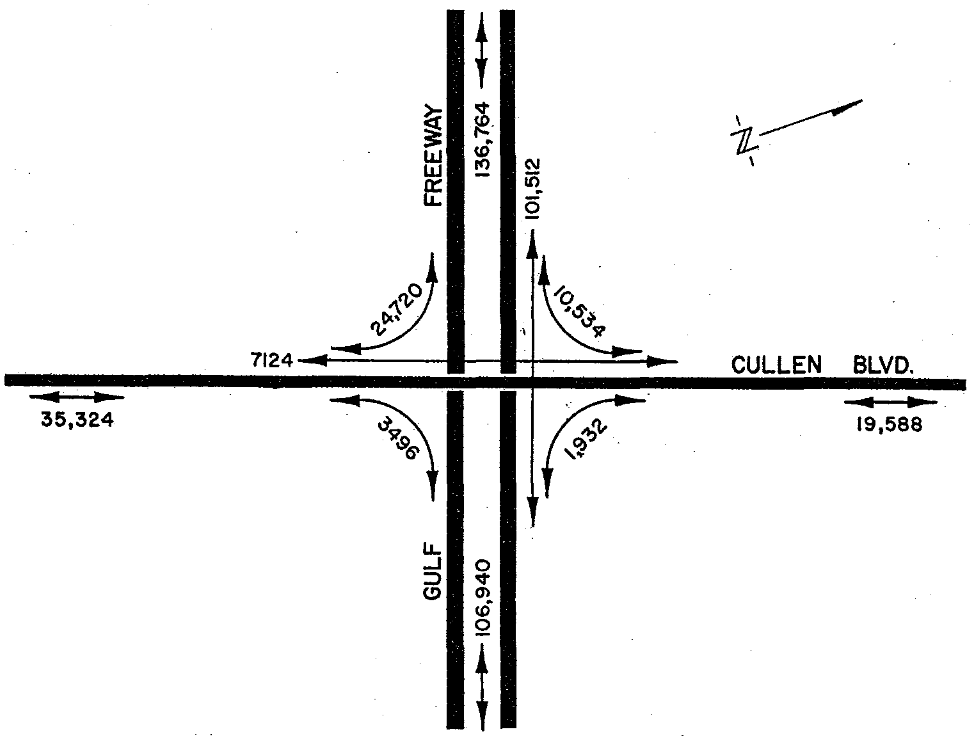


SEMINARY DRIVE INTERCHANGE

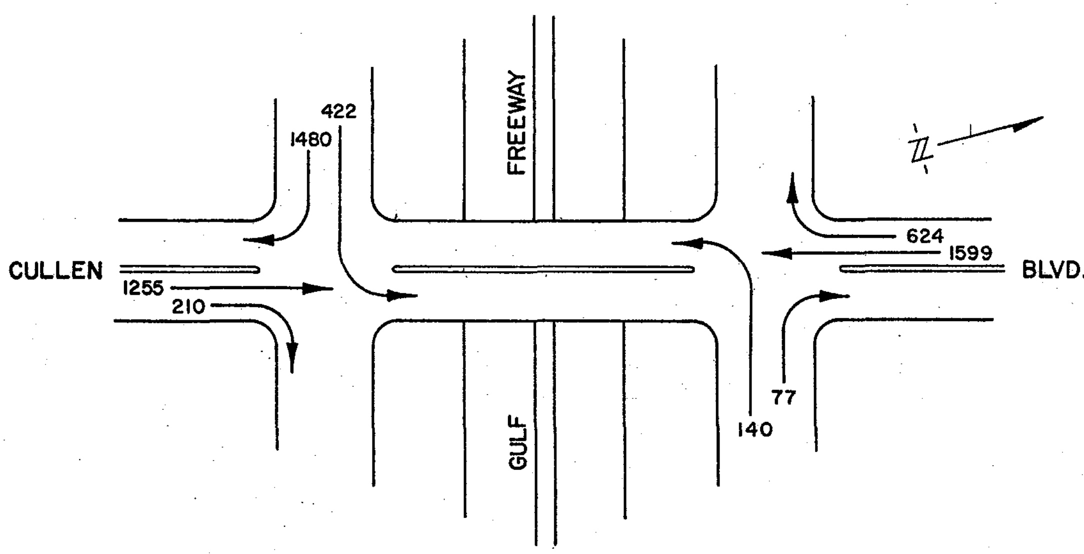
I.H. 35W

FORT WORTH, TEXAS

FIGURE 27



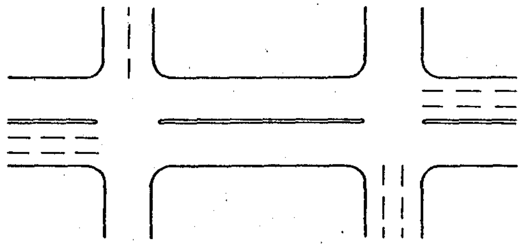
ESTIMATED ADT (1980)



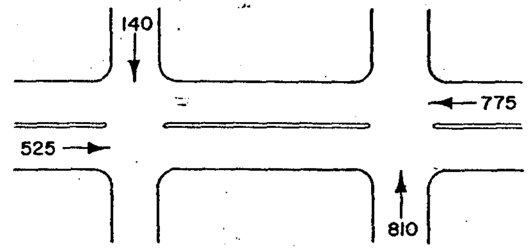
ESTIMATED HOURLY VOLUMES (1980)
P. M. PEAK

FIGURE 28

STEP I – ASSUME A DESIGN BASED ON TRAFFIC MOVEMENTS SHOWN IN FIGURE 28.

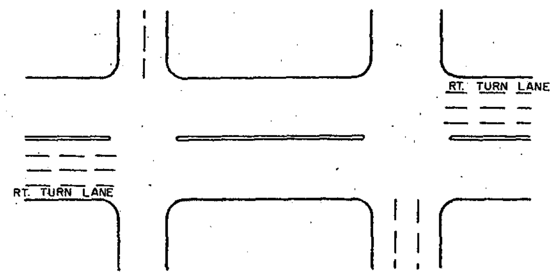


STEP II – DETERMINE CRITICAL LANE VOLUMES FOR EACH OF THE APPROACHES IN THE ASSUMED DESIGN.

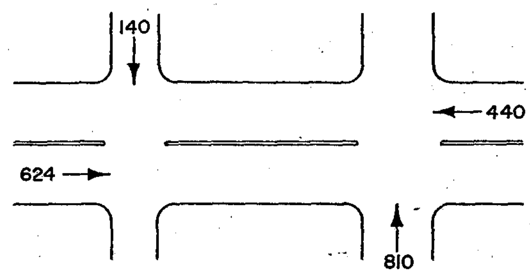


SUMMATION OF CRITICAL LANE VOLUMES
= 775 + 140 + 525 + 810 = 2250
ADJUSTMENT FOR PEAK PERIOD: 2250 x 1.15 = 2588
COMPARE TO CRITICAL VOLUME: 2588 > 1650
THEREFORE, THE ASSUMED DESIGN IS INADEQUATE.

STEP III – ASSUME A REVISED DESIGN TO REDUCE THE CRITICAL LANE VOLUMES



STEP IV – DETERMINE CRITICAL LANE VOLUMES FOR THE REVISED DESIGN.



SUMMATION OF CRITICAL LANE VOLUMES
= 624 + 140 + 440 + 810 = 2014
ADJUSTMENT FOR PEAK PERIOD: 2014 x 1.15 = 2316 > 1650
THEREFORE, THE REVISED DESIGN IS INADEQUATE.
A HIGHER-TYPE DIRECTIONAL INTERCHANGE IS REQUIRED.

SAMPLE CALCULATIONS FOR DIAMOND INTERCHANGE
GULF FREEWAY AND CULLEN BOULEVARD
HOUSTON, TEXAS

FIGURE 29

SUMMARY

As a result of research work conducted by the Texas Transportation Institute on conventional-type diamond interchanges, it is concluded that this type 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.

ACKNOWLEDGMENT

Grateful acknowledgment 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.

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4. LeRoy, Holden M., and Jean W. Clinton, "Signalization of Diamond Interchanges," Proceedings, Institute of Traffic Engineers, 1960.

5. Moskowitz, Karl, "Signalizing a Diamond Interchange," Proceedings of the Northwest Traffic Engineering Conference, July, 1959.

APPENDIX

BERRY I DATA

CYCLE NO.	PHASE LENGTH	MOVEMENT "A"	MOVEMENT "B"	PHASE LENGTH	VEHICLE MOVEMENT	PHASE LENGTH	VEHICLE MOVEMENT	CYCLE LENGTH	TOTAL GREEN	TOTAL VEHICLES
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

TABLE I

BERRY II DATA

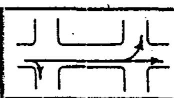
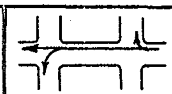
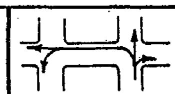
CYCLE NO.									CYCLE LENGTH	TOTAL GREEN	TOTAL VEHICLES
	PHASE LENGTH	VEHICLE MOVEMENT	PHASE LENGTH	VEHICLE MOVEMENT	PHASE LENGTH	VEHICLE MOVEMENT	PHASE LENGTH	VEHICLE MOVEMENT			
1	21	18	21	10	25	22	14	9	89	81	52
2	21	17	21	16	28	27	14	8	92	84	68
3	22	18	31	25	33	36	25	13	118	111	92
4	31	31	24	18	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	117	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

TABLE 2

BERRY III DATA

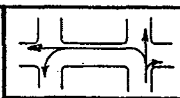
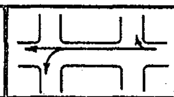
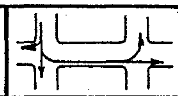
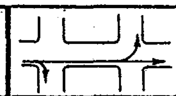
CYCLE NO.									CYCLE LENGTH	TOTAL GREEN	TOTAL VEHICLES
	PHASE LENGTH	VEHICLE MOVEMENT	PHASE LENGTH	VEHICLE MOVEMENT	PHASE LENGTH	VEHICLE MOVEMENT	PHASE LENGTH	VEHICLE MOVEMENT			
1	15	7	20	14	14	14	16	5	64	65	40
2	16	8	27	20	14	9	20	14	73	77	51
3	15	7	23	15	22	19	25	21	80	85	62
4	19	8	21	20	17	11	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	20	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

TABLE 3

FIXED TIME DATA

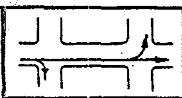
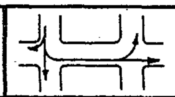
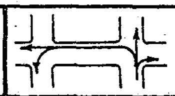
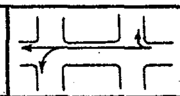
CYCLE NO.									CYCLE LENGTH	TOTAL GREEN	TOTAL VEHICLES
	PHASE LENGTH	VEHICLE MOVEMENT	PHASE LENGTH	VEHICLE MOVEMENT	PHASE LENGTH	VEHICLE MOVEMENT	PHASE LENGTH	VEHICLE MOVEMENT			
1	21	13	23	20	19	4	23	12	80	86	49
2	"	18	"	15	"	6	"	19	"	"	58
3	"	16	"	22	"	6	"	15	"	"	59
4	"	10	"	21	"	7	"	15	"	"	53
5	"	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

TABLE 4

OFF-PEAK DATA

(12:00 A.M.-01:00 A.M.)

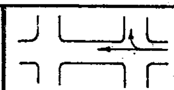
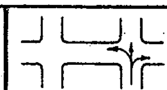
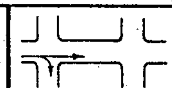
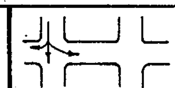
CYCLE NO.									TOTAL GREEN	CYCLE LENGTH	TOTAL VEHICLES
	PHASE LENGTH	VEHICLE MOVEMENT	PHASE LENGTH	VEHICLE MOVEMENT	PHASE LENGTH	VEHICLE MOVEMENT	PHASE LENGTH	VEHICLE MOVEMENT			
1	17	0	0	0	34	1	14	3	65	69	4
2	16	0	14	1	14	4	14	2	58	60	7
3	16	0	14	1	12	1	14	3	56	57	5
4	15	4	14	1	12	3	14	1	55	57	9
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	38	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

TABLE 5