AN ANALYSIS OF DIAMOND INTERCHANGE SIGNALIZATION

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This paper presents a systematic approach to the signalization of diamond interchanges. Attention is directed so that the resulting signalization concepts are applicable to the real-time control of diamond interchanges, which is the ultimate objective of this project. This paper provides a critical review of the existing practices for diamond interchanges. One of the principal products of this study is the identification of all the basic elements that constitute a phasing pattern. Each of the phasing patterns is then described by a set of parameters that have one-to-one correspondence with the signal-controller adjustments. These basic phasing parameters are used as aids to develop and synthesize the various possible phasing patterns. After each phasing pattern developed is evaluated, 2 preferred sets of phasing patterns are identified and a typical diamond interchange phasing pattern from the field is described. Applicability of these phasing concepts to the real-time control of diamond interchanges is also discussed. Finally, operational characteristics of full diamond interchanges from signalization data available for the city of Los Angeles are presented.

•THE GOAL of this research study was to determine an objective way of signalizing a diamond interchange in order to obtain high levels of operational performance. Attention was directed not only to fixed signalization concepts but also to concepts applicable to the real-time control of diamond intersections, which is a long-term objective of a broader research program on signalized diamond interchanges currently under way.

There are approximately 100 full diamond interchanges and another 100 partial diamond interchanges in the Los Angeles metropolitan area, about half of which are signalized. This sample gives an indication of the national incidence of this type of interchange in urbanized areas and emphasizes the importance of providing good signal control at such facilities. However, there seems to be anything but full agreement regarding the best way to signalize a diamond interchange. This is probably due to the lack of a methodology to address the problem, although we note that significant attempts have been made to structure such a framework.

In performing this study, we made an investigation of the principal and distinctive characteristics of phasing patterns for signalized diamond interchanges. A systematic review was made of the pertinent literature, and an operational study was conducted on signalized diamond interchanges in order to identify major signalization parameters and to determine their degree of correspondence with the signal-controller adjustable variables. With the identification of all these basic elements, any possible phasing pattern can be synthesized.

The Los Angeles Department of Traffic, generally considered a user of good signalization practice, provided signal timing and other pertinent information for local signalized diamond interchanges. This set of data has formed the basis for a detailed investigation into phasing patterns. Attention was limited to full diamonds signalized at both ramp intersections, which is, of course, the most difficult case.

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DEFINITIONS

The following definitions are used in this paper.

A phase is defined as a distinct state of a traffic signal or set of signals, where distinct signal light states (green, red, or amber) are attached to each direction of flow. Traffic engineers use the term "phase" in 2 distinct ways in describing each different state of traffic movement when referring to (a) a phasing pattern of a diamond interchange complex or (b) the signal activation of distinct traffic movements at an individual intersection. However, the meaning of the term is believed to be clear in each instance that it is used in this paper.

A traffic movement is the distinct entry or exit mode of vehicles that requires a green traffic signal at an intersection.

A phasing pattern is a combination of different phases, including all the possible traffic movements of the intersection or set of intersections (diamond interchange) where any traffic movement can extend for more than one consecutive phase but no traffic movement is generally repeated twice through a separation of amber and red lights within a given cycle.

BASIC TYPES OF CURRENT PHASING PATTERNS

Of the various possible phasing patterns or phasing sequence (1) types, 3 phasing patterns are most frequently cited: Two are 3-phase patterns, and one is a 4-phase pattern with 2 overlaps. Figures 1 and 2 show the 2 kinds of 3-phase phasing patterns. Figure 3 shows the 4-phase phasing pattern with 2 overlaps, and Figure 4 shows the 4-phase pattern with no overlaps.

In fact, there are only 3 distinct phases at each diamond ramp intersection, making a total of 9 distinct possible phases, called the 9 basic phases, for the 2-ramp intersections of a diamond interchange. Detailed descriptions of the 9 basic phases are given in the following and shown in Figure 7. For purposes of comparison, the 9 basic phases are also shown in Figures 1 through 5. The WALK, flashing DON'T WALK (WAIT), and steady DON'T WALK (WAIT) phases for pedestrians, as well as the amber phases for motorists, have been excluded from these and all of the phasing patterns discussed in this paper. However, these movements can be accounted for by the application of the same principles.

Three-Phase Phasing Pattern

The 3-phase phasing pattern shown in Figure 1 seems to give preference to the straight-through traffic on the arterial street. The left-turning vehicles on the arterial

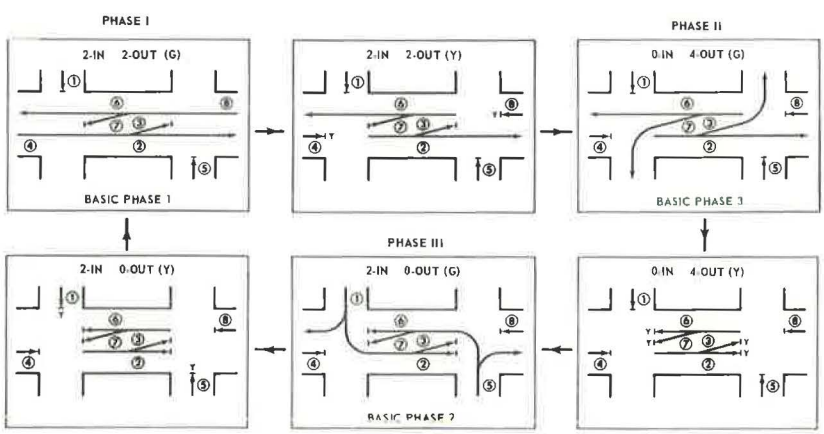

Figure 1. Three-phase phasing pattern, fully symmetrical.

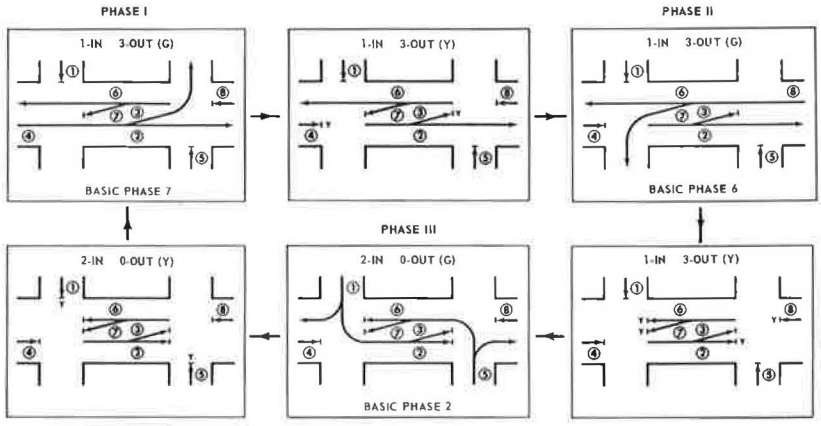

Figure 2. Three-phase phasing pattern, partly symmetrical.

are stored during Phase I and only begin to clear in Phase II when the incoming traffic from the arterial to the diamond is stopped. During Phase II, the stored left-turn vehicles are cleared. The number of such vehicles is limited by the storage capacity of the diamond. During Phase III, the left-turning off-ramp traffic is again limited by the storage capacity of the diamond. Note that this type of phasing pattern is symmetrical for both directions of traffic movement; e.g., in Phase I, the 2 straight-through traffic movements are given the same green time. This type of phasing pattern seems suitable where there is heavy traffic movement on the straight-through arterial street in both directions and where there is very little traffic coming from the freeway through the off-ramps and entering the freeway from the arterial street through the on-ramps.

The second kind of 3-phase phasing pattern shown in Figure 2 also has limited storage capacity for the off-ramp traffic (Phase III). During Phase I, the initial green

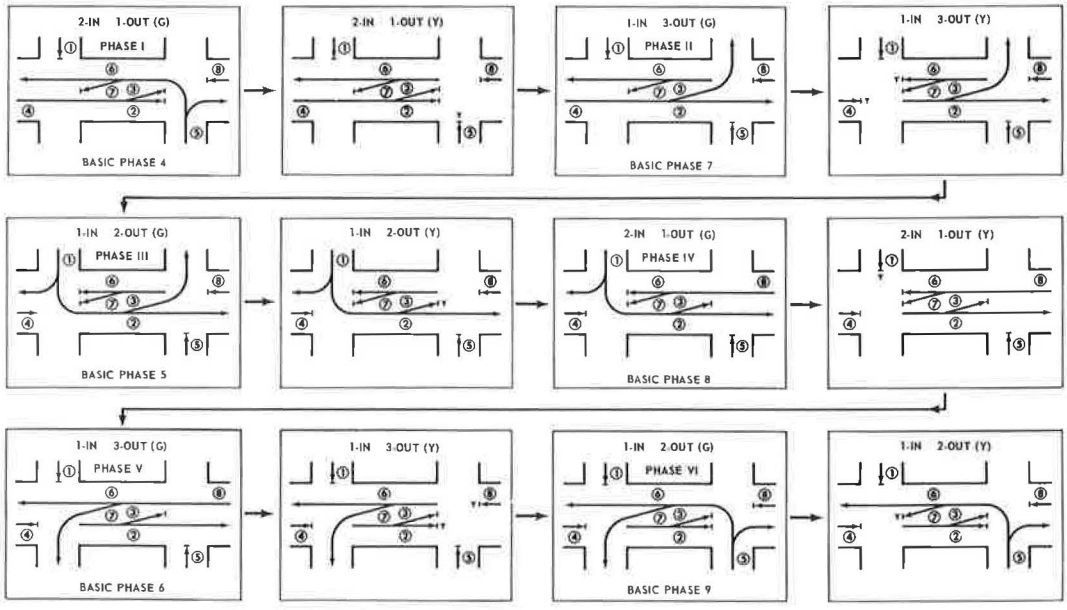

Figure 3. Four-phase phasing pattern with 2 overlaps.

period for movement 4 will be of little use because it will still take some time before the last vehicle in the interior approach queue starts moving because of the response times of all the vehicles in front of it. At the same time, vehicles will be discharged in movement 6 during this time period without any input of vehicles. During Phase II, when the green signal is given for movement 8, the interchange will be practically empty. During Phase III, cars are not completely cleared in the internal movements 6 and 7 of the arterial traffic of Phase II, before the off-ramp traffic starts moving inside the diamond interchange. It may again be observed from this phasing pattern that the green times allocated for different movements are symmetrical in each phase. For example, the green times for movements 4 and 3 in Phase I are the same. Pinnell and Capelle (2) have pointed out that clearance phases should be added following Phases I and II to clear the interior approaches for storage of the off-ramp traffic coming from the freeway in Phase III. As shown in Figure 5, they used this type of phasing pattern in their operational study of signalized interchanges in the Berry I study.

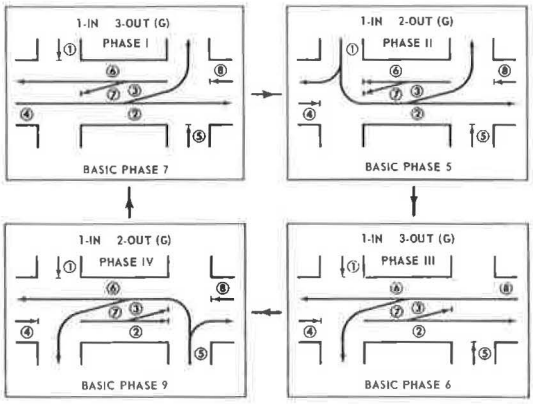

Figure 4. Four-phase phasing pattern with no overlaps.

Four-Phase Phasing Pattern With Overlap

The other phasing pattern widely discussed in the literature is the 4-phase with overlap shown in Figure 3. As the name implies, 2 movements that would normally be conflicting without the spacing between the 2 intersections of the diamond are given a green signal simultaneously. Phases I and IV are the overlap phases (Fig. 3). The main features of this type of phasing pattern are the nearly continuous movement of straight-through traffic between the 2 intersections of the diamond and the virtual elimination of stopped vehicles in the interior approaches. However, the lengths of the overlap phases are very critical to the efficient operation of this scheme. The overlap phases can operate effectively only if the traffic entering the interchange from both the arterial approach and an off-ramp approach maintain a continuous progression without running into the red signal at the other intersection or encountering waiting vehicles between the intersections.

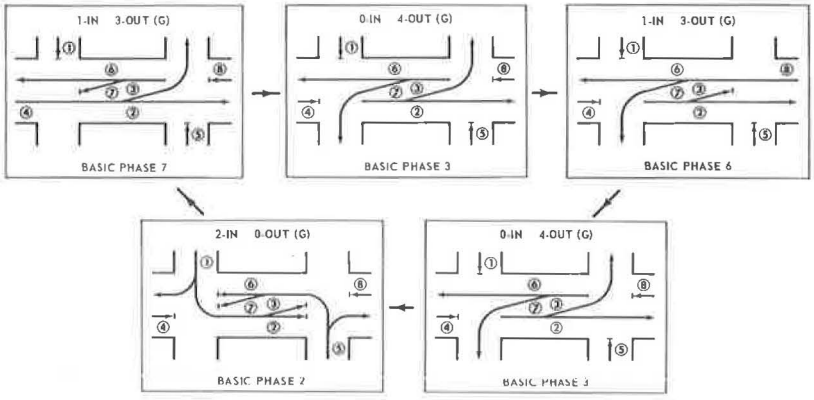

Figure 5. Three-phase phasing pattern with 2 clearance phases.

Four-Phase Phasing Pattern Without Overlap

Figure 4 shows the 4-phase phasing pattern with no overlap phases used by Pinnell and Capelle (2) in their Berry II study of the diamond interchange. Comparison of this phasing pattern with the 4-phase-with-overlap phasing pattern reveals some interesting advantages in the latter. For example, Figure 4 shows that, in Phase I of the 4-phase phasing pattern, the signals for movements 4, 2, and 3 turn green simultaneously at the beginning of the phase. The green signals for movements 2 and 3 produce little advantage to the traffic movement in the early seconds of this phase inasmuch as there are no vehicles to be served because the interior space of the diamond was cleared earlier in Phases II and III. In the 4-phase-overlap phasing pattern this time period is allotted to the overlap phase, where traffic signals for movements 2 and 3 stay red and the off-ramp movement 5 continues green.

MERITS OF DIFFERENT PHASING PATTERNS

Critique on Limitations of 4-Phase-Overlap Signalization

Certain contradictory statements in publications on diamond signalization may be added to the differences of opinion over the choice of phasing patterns. As an example, Woods (3) points out some limitations of the 4-phase-with-overlap phasing pattern. Regarding the first limitation, Woods comments, "The four-phase signal system illustrated in Figure 1 can only show an advantage over a three-phase system if the amount of overlap is greater than the time lost in the added clearance phase and starting delay." (Figure 1 in the quote refers to 4-phase with 2 overlaps and is equivalent to Figure 3 in this paper.)

A closer inspection of the 4-phase-overlap and the 3-phase phasing patterns shown in Figures 3, 1, and 2 reveals that there is no added lost time in the clearance phase or the starting delay in the overlap phase. In every cycle each movement in these phasing patterns is given only 1 green signal, followed by an amber period. Because the 8 movements shown in the various phasing patterns are given only 1 continuous green signal every cycle, the vehicles corresponding to each of these movements experience only 1 starting delay; similarly, only 8 clearance intervals correspond to these 8 traffic movements. In the 3-phase phasing pattern these amber signals for the 8 movements occur in the 3 clearance phases, while in the 4-phase-overlap signalization they occur in 6 clearance phases. However, the lost time in clearing the traffic in all these phasing patterns remains unchanged. As a matter of fact, as pointed out by Spitz (4), the starting delay for movements 2 and 6 is effectively reduced to a minimum for the 4-phase-overlap signalization.

Critique on Cycle Length and Capacity of Diamond Interchange

Another statement made by Woods (3) refers to the cycle length and the capacity of the diamond interchange. Woods concludes by commenting, "... since the system is more than 100 percent efficient, the more cycles that can be completed in a given time period, the greater the capacity of the system, i.e., use of very short cycles is desirable." He builds this argument by starting, "The inclusion of an overlap phase means that a period of time equal to the length of the overlap is available to offset the time lost during the amber phases." He then gives the following relationship for total effective green time for the 4-phase-with-overlap phasing pattern: "Effective green time = cycle length - 4 (length of amber phase) + 2 (length of the overlap)." Length of the overlap takes into account the time periods of the green and amber phases associated with the overlap phase. Referring to these relationships, Woods states, "... when the overlap time is equal to twice the length of the amber phase the effective green time is equal to the cycle length. Increasing the overlap to more than twice the length of the amber phase results in an effective green time greater than the length of the cycle, i.e., more than 100 % efficient."

From this he concludes that the system is more than 100 percent efficient, and the more cycles that can be completed per given time period, the greater the capacity will be. A closer look at the effective green time indicates that it is the sum of the green

time for movements 1, 4, 5, and 8. Note that many phasing patterns other than that considered by Woods will have green time for movements 1, 4, 5, and 8 greater than the cycle length and, according to Woods' arguments, would be more than 100 percent efficient. Hence, this type of analysis of phasing patterns might be misleading.

Actually, the capacity of the diamond interchange for any phasing pattern will increase as the cycle length is increased. This has been acknowledged by Ridgeway (5). Use of the minimum cycle length, however, is recommended for different reasons. Webster (6) and others have indicated that the minimum cycle length that will handle the traffic volumes will minimize the delay.

Critique on Coordination of Diamond Intersection Signals With Nearby Arterial Signals

Another feature of diamond interchange signalization is the relative value of coordination of the diamond intersections with signals of the nearby intersections of arterial streets. Pinnell and Capelle (2) note the desirability of maintaining the progression of the through-traffic but cite the diamond interchange area as a bad timing point in the coordinated system because the signal system at the interchange must operate in a multiphase sequence. They further argue, "The through-traffic for which progression is desired represents a minor percentage of the total traffic entering the interchange area."

This through-traffic was approximately 25 percent of the total interchange traffic when they performed the analysis of volume counts for the Berry Street interchange in Fort Worth and the Cullen and Wayside interchanges in Houston. They conclude by remarking, "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 [arterial street]."

However, others tend to disagree with these remarks. For example, Hutchison (7), of the Los Angeles Department of Traffic, remarks, "It is an absolute must that these adjacent intersections be controlled at peak efficiency and be interconnected to the controls at the freeway ramps." Skiles (8), also of the Los Angeles Department of Traffic, points out that most of the diamond interchanges in Los Angeles are located near a signal-controlled arterial intersection at distances which vary from 200 to 1,000 ft. Under these spacing conditions, he points out that coordination with adjacent signals is essential and further comments,

> Usually, coordination approaching the interchange has been the most critical because of the effect of starting delay at the beginning of the input green interval. . . . Unfortunately, as intersection spacing reduces, effective coordination becomes increasingly difficult. . . . in most applications, the importance of signal coordination is not to provide coordinated flow through the interchange, although that may be a secondary benefit. The value is in improving overall interchange operation by improving the flow into and out of the interchange.

Eckhardt (9), of the California Division of Highways, comments, "Coordination is of little or no value unless traffic can be handled. If a lack of capacity results in an accumulated backup of traffic, then the value of coordination is lost. If efficiency at the diamond intersections is sacrificed in an attempt to maintain coordination, . . . then no reason for coordination exists."

Similar opinions exist in favor of and against the coordination of diamond intersections with arterial streets. Generally, people working for the city tend to favor the coordination, while those responsible for freeway systems support effective handling of traffic from the off- and on-ramps by the diamond interchange. The usual conclusion is that greater attention should be given to coordination of diamond intersections with the nearby arterial intersection where the traffic volume from the arterial street constitutes a large percentage of the total traffic feeding the diamond.

Until now we have talked about various phasing patterns where the traffic volumes in the 2 through-directions, the 2 off-ramps, and the 2 left-turn lanes are of approximately the same magnitude. In real-life, variations exist that along with other considerations of the diamond, can result in several phasing patterns.

BASIC SIGNAL-PHASING CONCEPTS OF DIAMOND INTERCHANGES

As stated earlier and shown in Figures 1 through 5, there are only 9 distinct basic signal phases. We will now examine the basis that constitutes a phase. We will then show that there are, indeed, 9 basic phases at the diamond interchange that form the basis for all the phasing patterns and that these constitute an exhaustive set.

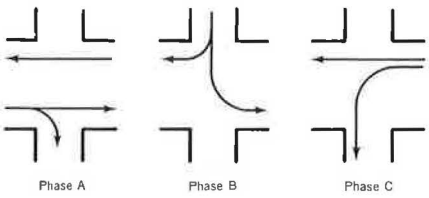

Figure 6. Three basic phases at individual ramp intersections.

Three Basic Phases at Individual Ramp Intersection

Let us now look at the left-ramp intersection of the diamond interchange shown in Figure 6 and see how many different signal phases this intersection can have where there will be no conflicts between movements. One phase at this intersection would exist when the off-ramp and the left-turn traffic from the arterial is stopped and the straight-through traffic is moving. We call this Phase A, as shown in Figure 6. Another phase results when the traffic from the off-ramp is given a green signal. To do this we have to stop all other movements at this intersection. We call this Phase B. The other phase occurs when arterial left-turn traffic is given a green signal. To obtain this, we have to stop all the incoming conflicting arterial traffic that may feed the diamond at this intersection. This is called Phase C. We can readily conclude that there are no additional phases at this intersection. In addition, there are only 3 similar basic phases at the right-ramp intersection of the interchange; these form the basis for all different possible phasing patterns. Furthermore, it follows that these 3 phases at the individual diamond intersections, in different combination, produce the 9 basic phases for the configuration covering both diamond intersections.

Nine Basic Phases at Diamond Interchange

Juxtaposition of the 3 basic phases of one intersection with the similar counterpart phases of the other intersection gives the 3 symmetrical phases designated as basic

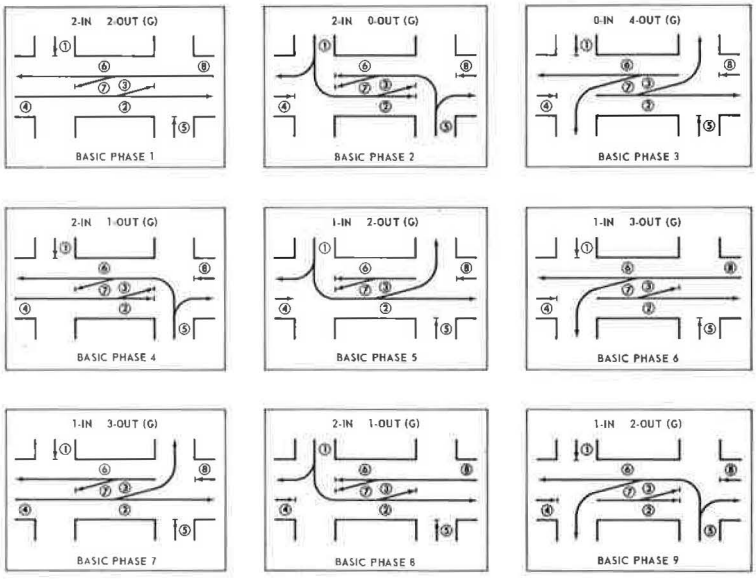

Figure 7. Nine basic phases.

phases 1, 2, and 3 and shown in Figure 7. We refer to these phases as the symmetrical phases because the traffic movements at one intersection are similar to those at the other intersection. Note that these phases constitute the 3-phase phasing pattern shown in Figure 1.

Again, corresponding to each of the 3 phases at one intersection are 2 dissimilar phases at the other intersection. Juxtaposition of these phases will give 2 sets of 3 asymmetrical phases. They are designated as basic phases 4, 5, 6, 7, 8, and 9 and are shown in Figure 7. The combination of these phases is arranged to constitute the 4-phase-overlap phasing pattern.

Thus, we have 3 basic phases at each ramp intersection that together constitute the 9 basic phases for the diamond interchange and that form the basis for all possible phasing patterns. We will now examine the function of each of these basic phases.

Characteristics of 9 Basic Phases at Diamond Interchange

As Figure 7 shows, we have a total of 8 traffic movements in the diamond interchange. We will refer to movements 1, 4, 5, and 8 as the external movements, which feed the diamond, and to movements 2, 3, 6, and 7 as the internal movements, which clear traffic out of the diamond. We will now characterize each phase in terms of how many external movements are feeding the diamond and how many internal movements are clearing the diamond. Thus, phase 1 (Fig. 7) has 2 external movements, 4 and 8, feeding the diamond, while 2 internal movements, 2 and 6, clear the diamond. In abbreviated form, we can write this as 2-in, 2-out, where in refers to the external approaches, out refers to the internal approaches, and the number before the words indicates the number of approaches involved in feeding or clearing the diamond.

Therefore, we can characterize the 9 basic phases in terms of the number of traffic movements coming into and out of the diamond. These are given in Table 1.

Arrangements of 3 Basic Phases at Individual Ramp Intersections

We will now examine the 3 basic phases at each intersection of the diamond to determine the different ways in which they can be arranged. We readily see that they can be arranged in only 2 distinct ways, ABCABC or ACBACB. There is no other way to arrange these 3 basic signal phases. In the ABCABC (or CAB or BCA) arrangement, first, the straight-through and the left-turn movements begin at the same time; later, the left-turn movement is stopped, while the straight-through movement continues to move. We call this arrangement the leading left turn. Here, Phase C precedes Phase A. The other arrangement, ACBACB (or BAC or CBA), is called a lagging left turn, and here Phase C follows Phase A. Therefore, the 3 basic phases at an individual intersection of the diamond can be arranged in only 2 different ways, the leading left turn and the lagging left turn.

Through combinations of the 2 intersections, these 2 kinds of phasing arrangements will give all the possible types of phasing patterns. Once the 3 basic phases have been arranged at each intersection of the diamond, different ways for their juxtaposition with the other intersection can be accomplished by using only one other parameter, the offset. In this paper, an offset for the diamond has been defined as the time difference in seconds between the starting green time of movements 4 and 8 of the diamond interchange (Fig. 7). This time difference can also be expressed in terms of the percentage of the cycle length of the diamond signal.

TABLE 1

BASIC PHASES IN TERMS OF TRAFFIC MOVEMENTS

Phase	Operational Function	Movements at Green Signal
1	2-in, 2-out	2, 4, 6, 8
2	2-in, 0-out	1, 5
3	0-in, 4-out	2, 3, 6, 7
4	2-in, 1-out	4, 5, 6
5	1-in, 2-out	1, 2, 3
6	1-in, 3-out	2, 6, 7, 8
7	1-in, 3-out	2, 3, 4, 6
8	2-in, 1-out	1, 2, 8
9	1-in, 2-out	5, 6, 7

POSSIBLE PHASING PATTERNS

First of all, we will demonstrate the formation of the 4-phase-overlap phasing pattern shown in Figure 3. This can be formed if both intersections have leading

left turns and if the cycle of phases is shifted in such a way that the start of the cycle at one intersection takes place in the middle of the other intersection cycle. This is shown in Figure 8. The bars represent the sequencing of the 3 basic phases at each ramp intersection. At the left ramp intersection, Phases A and B move the traffic into the diamond, while Phases A' and C' move this traffic out of the diamond at the left ramp intersection (Fig. 6). The corresponding 4-phase-overlap phasing pattern that results from this arrangement is shown in Figure 3.

The formation of this 4-phase-overlap phasing pattern is also shown in a compact form in Case 1 of Figure 9. Cases 2 through 5 (Fig. 9) represent the formation of other possible types of phasing patterns that can result from different offsets when both of the ramp intersections have leading left turns. Case 2 represents the phasing pattern when the offset is 0 percent of the cycle length; Cases 3, 4, and 5 represent the phasing patterns when the offsets are ½, 1, and 2 phases in length respectively (where the phases are assumed to be uniform in length). The phasing patterns corresponding to Cases 2 through 5 are shown in Figure 10. This figure shows that the phasing pattern that results from the offset of 1 phase length is similar to that which results from the offset of 2 phase lengths (with the intersections reversed). Similarly, the phasing pattern that would result from the offset of 2½ phases would be similar to the one resulting from a ½ phase offset. Further inspection of this figure shows that none of these phasing patterns is as efficient as the one corresponding to Case 1 (4-phase-overlap).

Inefficiency results when cars in the internal approaches (movements 2, 3, 6, and 7) must wait unnecessarily, when there are no cars in the internal approaches to be served by the early seconds of a green signal and/or when cars in the external

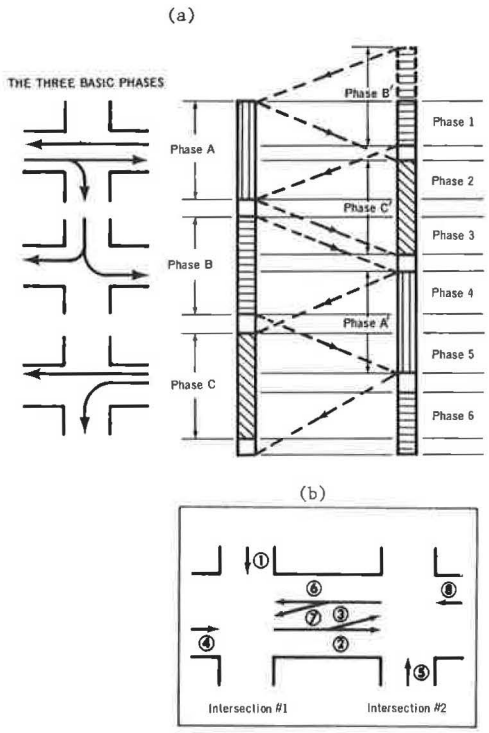

Figure 8. Formulation of 4-phase-overlap phasing pattern from 3 basic phases at each ramp intersection.

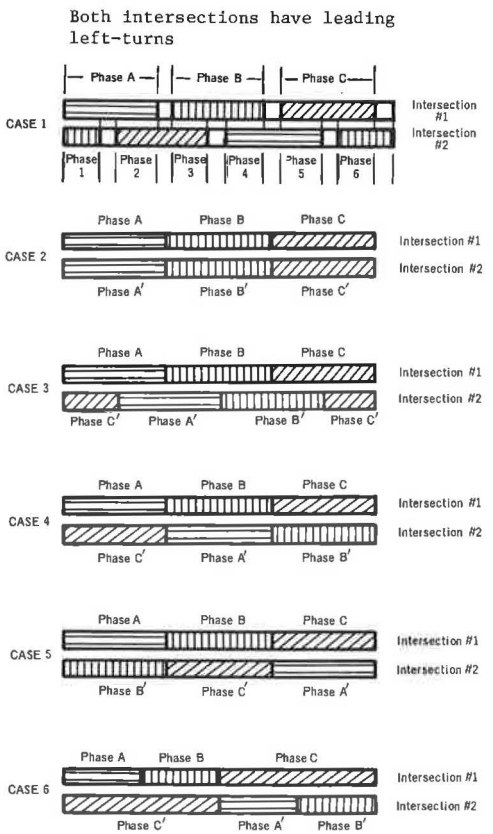

Figure 9. Formulation of various possible phasing patterns where both ramp intersections have leading left turns.

approaches (movements 1, 4, 5, and 8) cannot make efficient use of green signals because of insufficient space in the diamond to accommodate them.

However, it is not always possible to provide an ideal 4-phase-overlap phasing pattern in the field because of various demand and geometric constraints. An example of this is shown in Case 6 of Figure 9. This is a 4-phase-without-overlap phasing pattern shown in Figure 4. This phasing pattern results when both the intersections have leading left turns and, furthermore, the length of Phase C at each intersection (where there are left turns) is equal to the length of Phases A and B and superimposed on these phases at the other intersection. This arrangement again results in the starting of the cycle in each intersection at the middle of the cycle of the other intersection, except that here

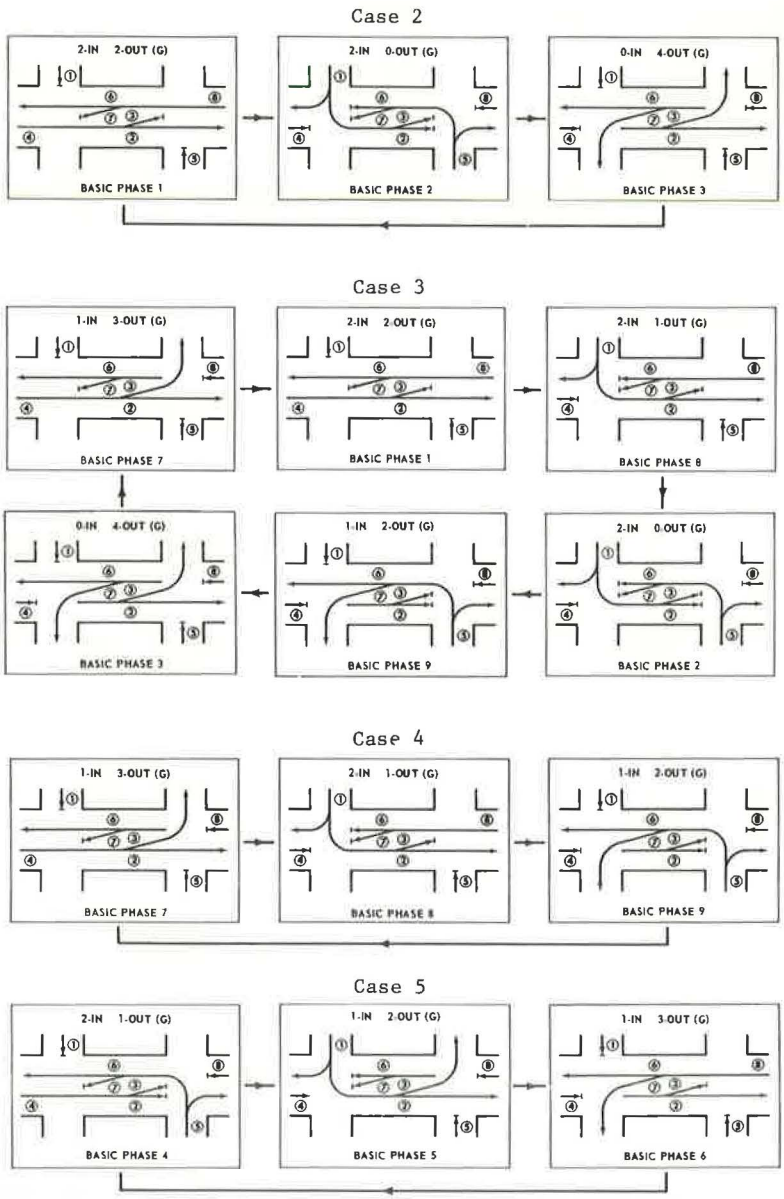

Figure 10. Phasing patterns where both ramp intersections have leading left turns.

the length of Phase C at each intersection is equal to the combined lengths of Phases A and B at the other intersection.

We will now examine the formulation of other possible types of phasing patterns where both intersections have lagging left turns. Case 1 shown in Figure 11 represents 0 offset—the simplest case. The phasing pattern that results from this arrangement is shown in Figure 1. Note that the 3-phase phasing pattern that results when both intersections have lagging left turns (Fig. 1) is better than the other 3-phase phasing patterns where both the intersections have leading left turns (Fig. 10, Cases 2, 4, and 5).

Cases 2 through 5 shown in Figure 11 represent the formation of other types of phasing patterns that can result from different offsets when both the intersections have lagging left turns. The various offsets considered in Cases 2 through 5 are ½, 1, 1½, and 2 phase lengths respectively (where phase lengths are assumed to be uniform). The corresponding phasing patterns that result from these arrangements are shown in Cases 2 through 5 in Figure 12. Note that the 3-phase phasing pattern with 0 offset (Case 1, Fig. 11) is more efficient than those obtained by other offsets (Cases 3 and 5, Fig. 11), when both intersections have lagging left turns.

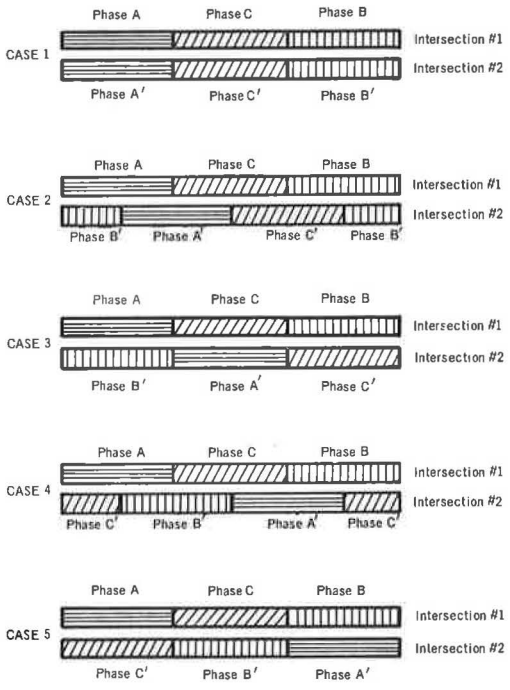

Figure 11. Formulation of various possible phasing patterns where both ramp intersections have lagging left turns.

Other possible types of phasing patterns occur where one ramp intersection has a leading left turn and the second ramp intersection has a lagging left turn. The inefficiency of these phasing patterns is evidenced by similar analysis. Thus, the various possible phasing patterns at diamond interchanges result from the following 4 arrangements of the 3 basic phases at each ramp intersection:

1. Two ramp intersections having leading left turns,
2. Two ramp intersections having lagging left turns,
3. The first ramp intersection having a leading left turn and the second having a lagging left turn, and
4. The first ramp intersection having a lagging left turn and the second having a leading left turn.

Each of these arrangements can have several different values of offsets and, corresponding to each arrangement with a given offset, a distinct phasing pattern.

We have determined 2 preferred sets of phasing patterns. One results when both intersections have a leading left turn and the offset is approximately 50 percent of the cycle length. The phasing patterns that result from this configuration belong to the general family of 4-phase-overlap phasing patterns. It may be pointed out that a correct time length within the constraints for each phase (especially the 2 overlap phases, Phases I and IV, Fig. 3) is important to the efficiency of the 4-phase-overlap phasing pattern.

The other preferred phasing pattern results when both intersections have lagging left turns and the offset is about 0 percent of the cycle length. The phasing patterns that result from this configuration belong to the general family of 3-phase phasing patterns. This pattern will be efficient when the traffic interacting with the freeway is only a small percentage of the overall traffic in the diamond interchange or when the overall traffic is very light. In the latter case, the storage capacity of the diamond,

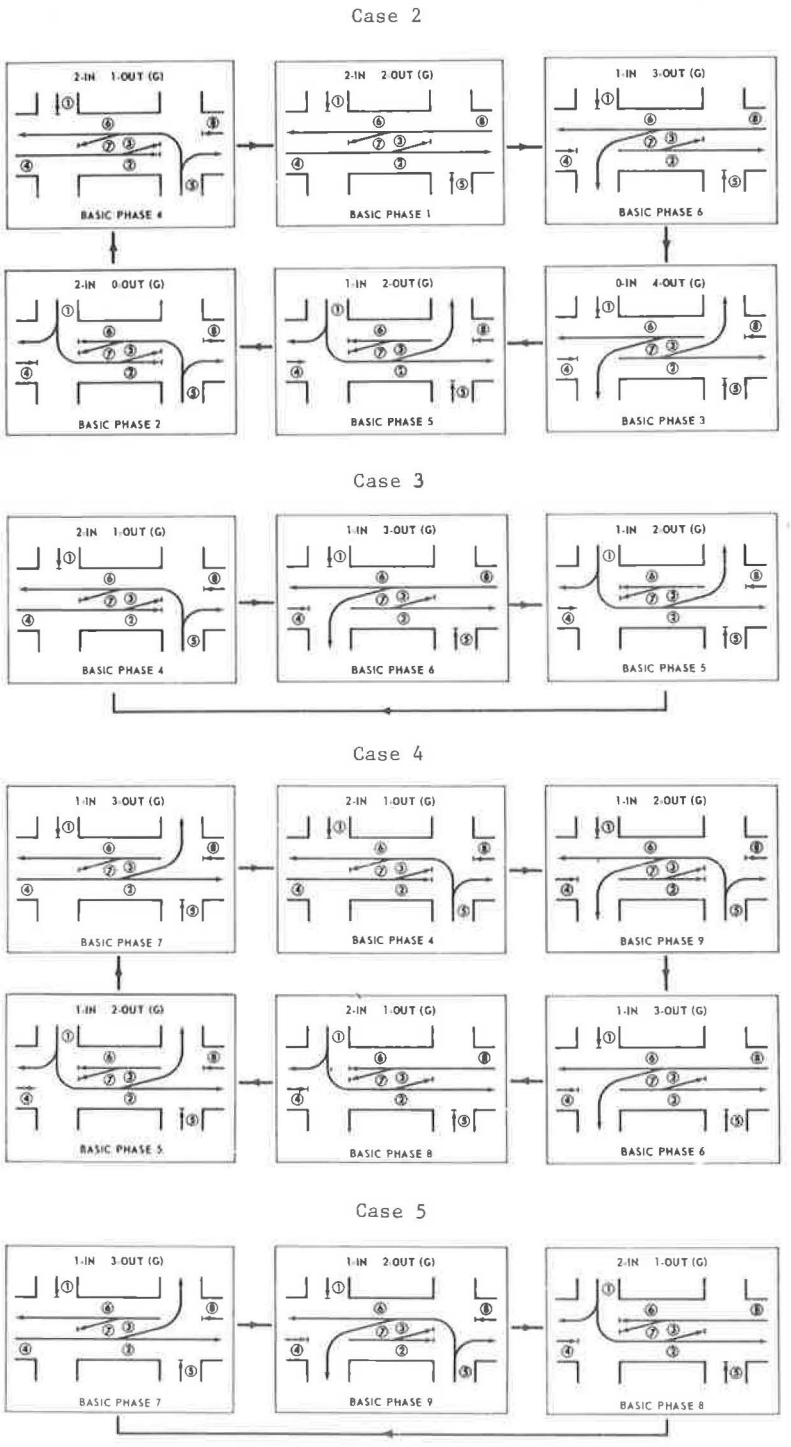

Figure 12. Phasing patterns where both ramp intersections have lagging left turns.

which normally restricts the lengths of Phases II and III (Fig. 1) in each intersection, is not critical because the cycle length is short.

A digital computer simulation model will determine the correct situations for the employment of each of these preferred phasing patterns.

REAL-TIME CONTROL OF DIAMOND INTERCHANGES

Unbalanced and nonuniform traffic demands and irregular geometric characteristics may require changes in the durations of the 3 basic phases (the time split) at each ramp intersection and make it impossible to adhere to the "ideal" fixed offsets for minimizing overall system delay. Furthermore, the especially complex and ever-changing character of the traffic in diamond interchanges makes it impossible to adhere to one set of phasing patterns (time splits, cycle lengths, sequencing, and offsets) and also obtain the highest possible efficiency for prevailing traffic conditions. Again, the degree of synchronization of the diamond ramp intersections with the arterial street signals should vary from time to time depending on the amount and percentage of drivers involved in the straight arterial movements. However, this coordination should also consider the effect on freeway traffic.

This study has analyzed all the possible signalization schemes that may be applied to the real-time control of diamond interchanges. Furthermore, the analysis given in this paper has specified the preferred set of phasing schemes that should be applied for real-time control of different traffic situations. A real-time control system may be defined as one that controls an environment by receiving measured data, describing the state of the environment, processing the data, and then using the results to execute an action that affects the environment with fast response time.

A control algorithm interlinks the measured data to the commanded action. A real-time control algorithm may be defined as a set of logical steps that control the traffic signals on a real-time basis by assigning a distinct control alternative (a means of activating the traffic signal system, where every traffic movement is given a specific amount of green time) to given traffic situations. These traffic situations are governed by a control strategy that determines the selection of the appropriate control alternative.

This analysis is being used in developing efficient real-time control algorithms, whereby different desired control alternatives (time splits, cycle length, sequencing, and offsets) will be applied on a continuous basis to match various traffic situations.

Several control algorithms have been developed (10) that determine the minimum cycle length that will handle traffic demands at each individual intersection in the system under consideration. The maximum of these minimum cycle lengths is taken as the common cycle length. Subsequently, green times (the splits) allocated for the basic phases depend on which algorithm is being used. These algorithms also determine the theoretical ideal offset for each pair of intersections (both leading, both lagging, or one leading and one lagging for full diamonds) by assigning proper weights to different intersections and to each direction in terms of its demand criticality.

These control algorithms are evaluated by a digital computer simulation model (11) that simulates traffic operations in a diamond interchange and is thus a powerful tool to measure the effectiveness of each control algorithm in terms of total system delay. This simulation model has been developed and validated according to macroscopic traffic statistics; that is, this model is accurate based on long-run statistics or large sample data. Another simulation model has also been developed (12, 13) that keeps track of the trajectory of each individual car and is thus accurate even in a small sample size.

The first simulation model, specially designed to evaluate real-time control algorithms is employed to filter out real-time control algorithms and to obtain fast simulation results. Based on this, an optimum set of control algorithms is chosen and a higher level evaluation obtained by using the second simulation model, which has more detailed mechanisms of car movements but requires longer simulation time.

FIELD EXAMPLES OF PHASING PATTERNS

Figure 13 shows the arrangement of the 3 basic phases for the Coldwater Canyon Avenue-Ventura Freeway interchange in Los Angeles and the time lengths of the phases

TABLE 2

OPERATIONAL CHARACTERISTICS OF SIGNALIZED DIAMOND INTERCHANGES IN LOS ANGELES

Interchange	Cycle Length (sec)	Offset		Green Time (sec)					
				Left Intersection			Right Intersection		
		Percent	Seconds	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
Ventura Freeway									
Whiteoak Avenue[a]									
Dial 1	60	43	25.8	15.0	12.0	24.0	24.0	15.0	12.0
Van Nuys Boulevard[a]									
Dial 1	60	53	31.8	21.0	10.2	19.8	23.4	11.4	16.8
Dial 2	60	47	28.2	21.0	10.2	19.8	21.0	16.2	13.8
Dial 3	60	50	30.0	21.0	12.0	18.0	23.4	11.4	16.8
Woodman Avenue[a]									
Dial 1	80	43	34.4	19.2	16.8	34.4	25.6	24.8	20.0
Dial 2	80	37	29.6	17.6	15.2	37.6	37.6	16.0	16.8
Balboa Boulevard[a]									
Dial 1	60	47	28.2	19.2	13.2	18.6	22.8	10.2	18.0
Dial 2	60	55	33.0	24.0	13.2	13.8	18.0	10.2	22.8
Coldwater Canyon[a]									
Dial 1	60	43	25.8	21.0	15.0	15.0	24.0	15.0	12.0
Dial 2	60	38	22.8	18.0	15.0	18.0	24.0	15.0	12.0
Dial 3	60	48	28.8	24.0	15.0	12.0	21.0	15.0	15.0
Laurel Canyon[a]									
Dial 1	60	50	30.0	21.0	12.0	18.0	21.0	12.0	18.0
Dial 2	60	51	30.6	16.8	16.8	17.4	21.6	10.8	18.6
Dial 3	60	56	33.6	23.4	13.2	14.4	16.2	13.2	21.6
Winnetka Avenue[a]									
Dial 1[f]	60	48	28.8	16.8	10.2	24.0	13.8	18.6	9.6
Dial 2[f]	60	39	23.4	10.2	10.2	30.6	15.6	15.0	7.2
San Diego Freeway									
Nordhoff Street[a]									
Dial 1	60	50	30.0	21.0	12.0	18.0	24.6	18.0	8.4
Roscoe Boulevard[a]									
Dial 1	60	49	29.4	24.0	9.0	18.0	21.0	18.0	12.0
Santa Monica Boulevard[a]									
Dial 1	60	44	26.4	23.4	16.2	11.4	25.8	16.8	8.4
Dial 2	60	42	25.2	18.0	21.0	12.0	19.8	22.2	9.0
Dial 3	60	57	34.2	19.8	16.2	15.0	25.8	16.8	8.4
La Tijera Boulevard[b]									
Dial 1	60	0	0.0	29.4	6.0	15.6	25.8	9.6	15.6
Dial 2	90	94	84.6	54.0	8.1	17.1	41.4	24.3	13.5
Dial 3	90	93	83.7	53.1	9.0	17.1	41.4	19.8	18.0
Hollywood Freeway									
Hollywood Boulevard[d]									
Dial 1	60	8	4.8	33.0	12.0	6.0	33.0	21.0	—
Alvarado Street[d]									
Dial 1	60	0	0.0	36.0	18.0	—	36.0	13.8	1.2
Magnolia Boulevard[e]									
Dial 1	60						36.0	18.0	—
Dial 2	60						36.0	18.0	—
Dial 3	60						30.0	24.0	—
Santa Monica Freeway									
Normandie Avenue[d]									
Dial 1									
Case 1	60	51	30.6	20.4	20.4	10.2	20.4	20.4	10.2
Case 2	60	52	31.2	20.4	20.4	10.2	20.4	20.4	10.2
Dial 2	80	49	39.2	36.0	16.8	17.6	32.0	16.8	21.6
Dial 3	80	42	33.6	34.4	17.6	18.4	41.6	16.8	12.0
Dial 4	60	51	30.6	20.4	20.4	10.2	20.4	20.4	10.2
Dial 5	80	50	40.0	28.8	20.8	20.8	36.0	17.6	16.8
Dial 6	80	57	45.6	36.8	16.8	16.8	27.2	17.6	25.6
Arlington Avenue[a]									
Dial 1									
Case 1	60	47	28.2	21.0	15.0	15.0	21.0	16.2	13.8
Case 2	60	0	0.0	21.0	15.0	15.0	21.0	16.2	13.8
Dial 2	80	51	40.8	35.2	16.8	18.4	37.6	16.8	16.0
Dial 3	80	55	44.0	36.8	16.8	16.8	29.6	29.6	11.2
Dial 4									
Case 1	60	37	22.2	21.0	15.0	15.0	21.0	16.2	13.8
Case 2	60	47	28.2	21.0	15.0	15.0	21.0	16.2	13.8
Dial 5	80	50	40.0	28.8	20.8	20.8	36.0	17.6	16.8
Dial 6	80	54	43.2	36.8	16.8	16.8	27.2	16.8	26.4

TABLE 2 (Cont'd)

Interchange	Cycle Length (sec)	Offset		Green Time (sec)					
				Left Intersection			Right Intersection		
		Percent	Seconds	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
Western Avenue[a]									
Dial 1									
Case 1	60	27	16.2	24.0	16.2	10.8	27.0	15.0	9.0
Case 2	60	0	0.0	24.0	16.2	10.8	27.0	15.0	9.0
Case 3	60	25	15.0	24.0	16.2	10.8	27.0	15.0	9.0
Dial 2									
Case 1	80	51	40.8	33.6	16.0	20.8	40.0	16.0	14.4
Case 2	80	52	41.6	33.6	16.0	20.8	40.0	16.0	14.4
Case 3	80	2	1.6	33.6	16.0	20.8	40.0	16.0	14.4
Dial 3									
Case 1	80	47	45.6	32.0	16.0	22.4	43.2	16.0	11.2
Case 2	80	39	31.2	32.0	16.0	22.4	43.2	16.0	11.2
Case 3	80	33	26.4	32.0	16.0	22.4	43.2	16.0	11.2
Vermont Avenue[a]									
Dial 1	60	49	29.4	18.0	22.8	10.2	16.8	22.8	11.4
Dial 2	80	40	32.0	23.4	33.0	14.6	23.4	33.0	14.6
Dial 3	80	50	40.0	23.4	33.0	14.6	23.4	33.0	14.6
Crenshaw Boulevard[c]									
Dial 1	60	20	12.0	24.0	12.0	15.0	20.4	20.4	10.2
Dial 2	60	28	16.8	27.0	15.0	9.0	30.0	10.2	10.8
Dial 3	60	23	13.8	27.0	12.0	12.0	28.2	14.4	8.4
Harbor Freeway									
Anaheim Street[a]									
Dial 1	60	50	30.0	27.0	15.0	9.0	27.0	15.0	9.0
Dial 2	60	55	33.0	24.0	15.0	12.0	18.0	15.0	18.0
Dial 3	60	50	30.0	21.0	15.0	15.0	24.0	15.0	12.0
Alondra Boulevard[a]									
Dial 1	60	50	30.0	24.0	14.0	12.0	24.0	15.0	12.0
Dial 2	80	43	34.4	35.2	19.2	16.0	30.4	16.0	24.0
Dial 3	80	42	33.6	26.4	24.0	20.0	38.4	16.0	16.0
Century Boulevard[a]									
Dial 1	60	69	41.4	27.0	18.0	6.0	18.0	13.0	21.0
Dial 2	60	69	41.4	21.0	24.0	6.0	15.0	10.2	25.8
Vernon Avenue[a]									
Dial 1									
Case 1	60	54	32.4	21.0	18.0	12.0	27.0	18.0	6.0
Case 2	60	90	54.0	21.0	18.0	12.0	27.0	18.0	6.0
Dial 2									
Case 1	80	54	43.2	33.6	16.8	20.0	24.0	22.4	24.0
Case 2	80	91	72.8	33.6	16.8	20.0	24.0	22.4	24.0
Dial 3									
Case 1	80	88	70.4	36.8	19.2	14.4	32.0	22.4	16.0
Case 2	80	46	36.8	36.8	19.2	14.4	32.0	22.4	16.0
Dial 4									
Case 1	60	58	34.8	21.0	18.0	12.0	27.0	18.0	6.0
Case 2	60	90	54.0	21.0	18.0	12.0	27.0	18.0	6.0
Dial 5	80	93	74.4	26.4	17.6	26.4	26.4	26.4	17.6
Dial 6	80	61	48.8	36.8	19.2	14.4	30.4	20.8	19.2
Florence Avenue[d]									
Dial 1	60	0	0.0	34.2	19.8	—	22.2	12.0	13.8
Dial 2	60	0	0.0	30.0	24.0	—	25.2	12.0	10.8
Dial 3	60	0	0.0	28.2	25.8	—	19.2	12.0	16.8
Rosecrans Avenue[e]									
Dial 1	60			33.0	21.0	—			
Dial 2	70			42.0	21.0	—			
Dial 3	80			40.0	32.0	—			
Imperial Highway[c]									
Dial 1	60	82	49.2	27.0	18.0	6.0	27.0	6.0	18.0
Dial 2	60	80	48.0	22.8	19.7	9.0	22.8	9.0	19.2
Dial 3	60	80	48.0	22.8	19.2	9.0	22.8	9.0	19.2
Golden State Freeway									
North Broadway[c]									
Dial 1	60	72	43.2	29.4	12.0	9.6	24.0	12.0	15.0
Dial 2	90	76	68.4	43.2	15.3	20.7	45.9	15.3	18.0
Dial 3	90	90	81.0	52.2	12.6	14.4	38.7	20.7	19.8
Sunland Boulevard[a]									
Dial 1	60	47	28.2	21.0	15.0	15.0	21.0	15.0	15.0
Dial 2	60	47	28.2	15.0	15.0	21.0	24.0	15.0	12.0
Dial 3	60	47	28.2	24.0	15.0	12.0	18.0	18.0	15.0

[a]Left and right intersections leading left turn.
[b]Left and right intersections lagging left turn.
[c]One intersection leading and other intersection lagging left turn.
[d]One intersection has unprotected left turn (no Phase C) and other intersection leading left turn.
[e]One intersection has unprotected left turn (no Phase C) and other intersection traffic-actuated.
[f]Includes and extra Phase AB (dial 1, 6.0, and dial 2, 10.2) between Phases B and C, a situation where movement 5 has a right-turn green arrow, movement 8 is green, and movements 2 and 3 are red.

in relation to the various offsets for the different times of day. Note that the 3 basic phases at each intersection have been arranged in a leading left-turn order. Case 2 refers to January 15, 1970, when the signalization of this diamond interchange was last set. The offsets for the off-peak, morning peak, and evening peak periods (also referred to as dials) are 25.8, 22.8, and 28.8 sec respectively. Case 1 (Fig. 13) refers to August 20, 1969, when the offsets for the interchange were originally set. The old offsets for the 3 peak periods were 33, 30, and 36 sec respectively. Case 1A (Fig. 13) for the morning peak hours refers to a situation where the offset between the 2 intersections of the diamond interchange was changed from the original 30 sec to 33 sec.

Thus we see that, although the green time for each of the movements (1, 2, 3, 4, 5, 6, 7, and 8 in Fig. 8) does not change with the use of different offsets, we do get different phasing patterns. The efficiency of these different phasing patterns will vary for different offset values, even though the green time for each basic phase or movement and the arrangement of the 3 basic phases at each leading left-turn intersection remain the same. Thus, there can be numerous phasing patterns (depending on the different values of offsets) that will have the same green time for each movement. We have analyzed a case in which the offset is close to half the cycle length and both the

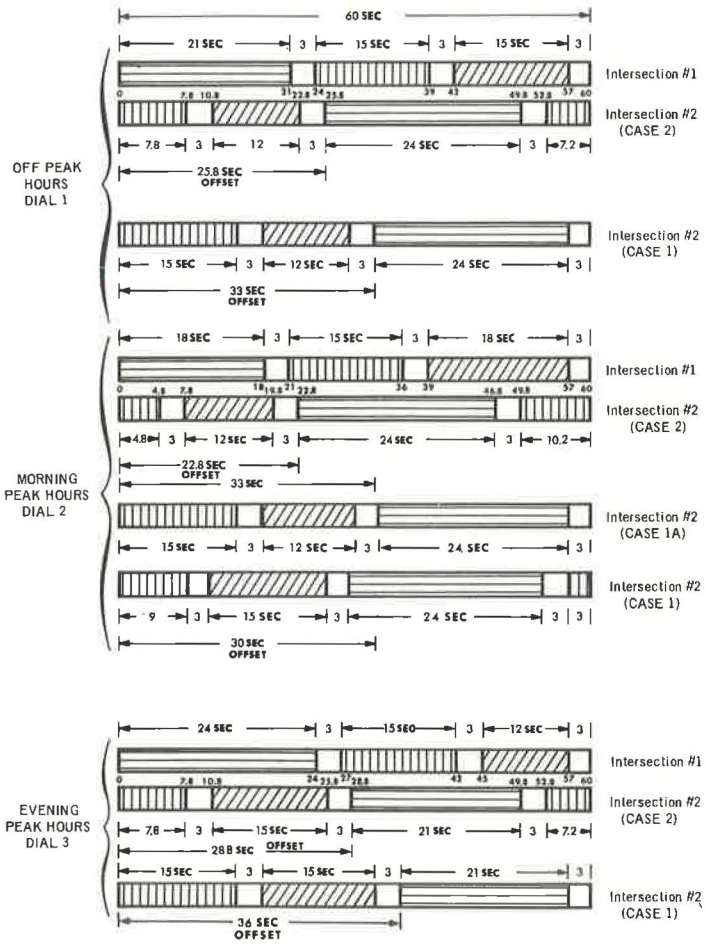

Figure 13. Formulation of different phasing patterns for Coldwater Canyon Avenue-Ventura Freeway diamond interchange.

intersections have leading left turns. This phasing pattern belongs to the family of 4-phase-overlap phasing patterns. Therefore, the value of the offset in terms of cycle length, the order in which the 3 basic phases have been arranged (leading left turn or lagging left turn), and the associated time lengths of the phases quite accurately describe the kind of phasing pattern resulting from a given situation.

Based on these parameters describing a phasing pattern, the timing charts of the various signalized full-diamond interchanges in the city of Los Angeles were studied, and it was found that almost all of these diamonds have leading left turns in both intersections, with offsets roughly on the order of one-half the cycle length. It is concluded, therefore, that the phasing pattern of most of these interchanges belong to the 4-phase-overlap family. An exception is the La Tijera-San Diego Freeway interchange, where both intersections have lagging left turns and the offset is close to full cycle length. Table 2 gives a summary of the investigation regarding full diamonds in the city of Los Angeles.

Of the 28 signalized full diamonds for which information is available at this time, only 1 diamond (La Tijera Boulevard-San Diego Freeway) has both lagging left turns; 3 diamonds (Crenshaw Boulevard-Santa Monica Freeway, Imperial Highway-Harbor Freeway, and North Broadway-Golden State Freeway) have 1 leading left turn and 1 lagging left turn; and 2 diamonds (Magnolia Boulevard-Hollywood Freeway and Rosecrans Avenue-Harbor Freeway) have an unprotected left turn (no Phase C) in one intersection and are traffic-actuated in the other intersection. Three diamonds (Hollywood Boulevard-Hollywood Freeway, Alvarado Street-Hollywood Freeway, and Florence Avenue-Harbor Freeway) have an unprotected left turn (no Phase C) in 1 intersection and leading left turn on the other intersection. The Winnetka Avenue-Ventura Freeway interchange includes an extra Phase AB between Phase B and C in its east ramp intersection. In this latter case, Phase AB refers to a situation where movement 5 has a right turn green arrow, movement 8 is green, and movements 2 and 3 are red.

For the 28 full diamonds, there are 92 dials. Sixty have cycle lengths of 60 sec, 27 have cycle lengths of 80 sec, 4 have cycle lengths of 90 sec, and 1 has a cycle length of 70 sec. Of the 67 dials having leading left turns in both intersections, 54 have offsets between 35 and 65 percent of cycle length (Vernon Avenue and Century Boulevard, both influenced by Coliseum traffic, provide the majority of offsets outside this range), 49 have offsets between 40 and 60 percent, and 35 have offsets between 45 and 55 percent of cycle length.

CONCLUSION

A systematic approach to the signalization of diamond interchanges has been developed by critically reviewing the existing practices used for signalizing diamond interchanges. A detailed analysis was made to identify all the basic elements that constitute a phasing pattern. After each of the phasing patterns had been described by a set of parameters that had one-to-one correspondence with the signal-controller adjustable variables, the various possible phasing patterns were developed and synthesized. An evaluation of each phasing pattern was made, and 2 preferred sets with respect to both efficiency and practicality were identified: one in which both intersections have leading left turns with offset about 50 percent of the cycle length, and one in which both intersections have lagging left turns with offsets of about 0 percent of the cycle length. One typical diamond interchange phasing pattern from the field was described. In addition, a summary was made of the set of parameters describing the operational characteristics of diamond interchange signalization in the city of Los Angeles.

These signalization concepts were developed for application to the development of a real-time control system, as well as for providing an objective and explicit basis for evaluating fixed signalization of diamond interchanges. This analysis is currently being used to develop real-time control algorithms in which different desired control alternatives will be applied on a continuous basis to match varying traffic situations, thereby promoting the efficient operational performance of diamond interchanges.

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