CHAPTER 26

INTERCHANGE RAMP TERMINALS

CONTENTS

EXHIBITS

I. INTRODUCTION

This chapter presents general material for analyzing interchange ramp terminals involving freeways, major highways, and urban streets. Although the chapter presents ideas and concepts relating to most types of interchanges that include two intersections, it focuses primarily on signalized, two-intersection diamond interchanges. The close proximity of the two signalized intersections forming the diamond creates interactive effects that complicate the analysis. A complete methodology for predicting the impact of these effects is not yet available; this chapter therefore is primarily conceptual in content.

TYPES OF INTERCHANGES

Several interchange types are recognized in the literature. The common types that may result in two closely spaced surface intersections are illustrated and discussed here. The single-point diamond interchange, with only one signalized intersection, also is illustrated. The term freeway is used here to denote a freeway, expressway, or a major through highway.

Diamond Interchanges

Most forms of diamond interchanges result in two or more closely spaced surface intersections, as illustrated in Exhibit 26-1. On a diamond interchange, only one connection is made for each freeway entry and exit, with one connection per quadrant. Left- and right-turning movements are used for entry to or exit from the two directions of the surface facility; diamond interchanges require left-turn movements. In rural areas, the junction of diamond interchange ramps with the surface facility is often controlled by stop or yield signs. If traffic demand is high, signalization becomes necessary.

There are many variations on the diamond interchange. The typical diamond has three subcategories defined by the spacing of the intersections formed by the ramp-street connections. Conventional diamond interchanges provide a separation of 240 m or more between the two intersections. Compressed diamond interchanges have intersections spaced between 120 m and 240 m, and tight urban diamond interchanges feature spacing of less than 120 m.

Split diamond interchanges have freeway entry and exit ramps separated at the street level, creating four intersections. Diamond configurations also can be combined with continuous one-way frontage roads. The frontage roads become one-way arterials, and turning movements at the intersections created by the diamond interchange become even more complex, due to the additional need to serve movements to and from the frontage road. Separated U-turn lanes also may be added, removing U-turns from the signal scheme, if there is a signal. A partial diamond interchange has fewer than four ramps, so that not all of the freeway-street or street-freeway movements are served. A three-level diamond interchange features two divided levels, so that ramps are necessary on both facilities to allow continuous through movements. Two interlocking split diamonds are created.

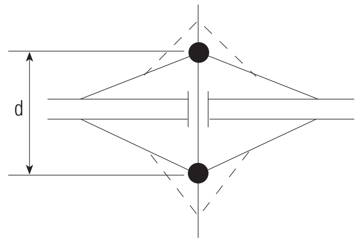
A single-point diamond interchange combines all the ramp movements into a single signalized intersection and has the advantage of operating as such. The design eliminates the critical issue of coordinating the operation of two closely spaced intersections.

All of these forms of diamond interchanges are depicted in Exhibit 26-1.

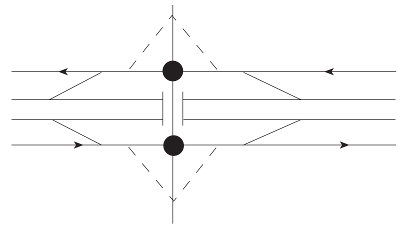
Partial Cloverleaf Interchanges

Partial cloverleaf interchanges—or parclos—are depicted in Exhibit 26-2. A variety of partial cloverleaf interchanges can be created with one or two loop ramps. In such cases, one or two of the outer ramps take the form of a diamond ramp, allowing a movement to take place by making a left turn. In some partial cloverleaf configurations, left turns also may be made onto or off of a loop ramp.

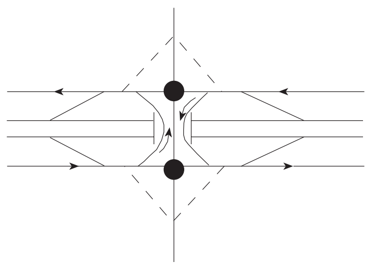
EXHIBIT 26-1. TYPES OF DIAMOND INTERCHANGES



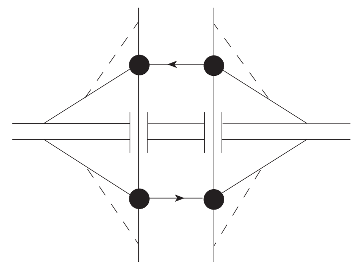
Conventional, d > 240 m
Compressed, d = 120–240 m
Tight urban, d < 120 m



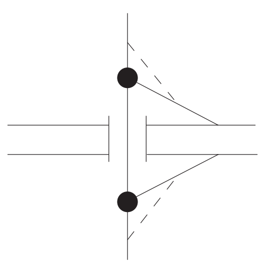
Diamond with continuous frontage roads



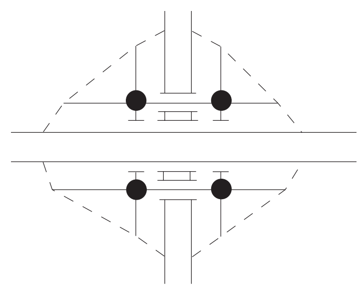
Diamond with U-turn lanes and service roads



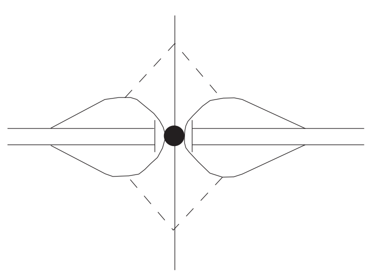
Split diamond interchange (cross roads, one- or two-way)



Partial (half) diamond interchange



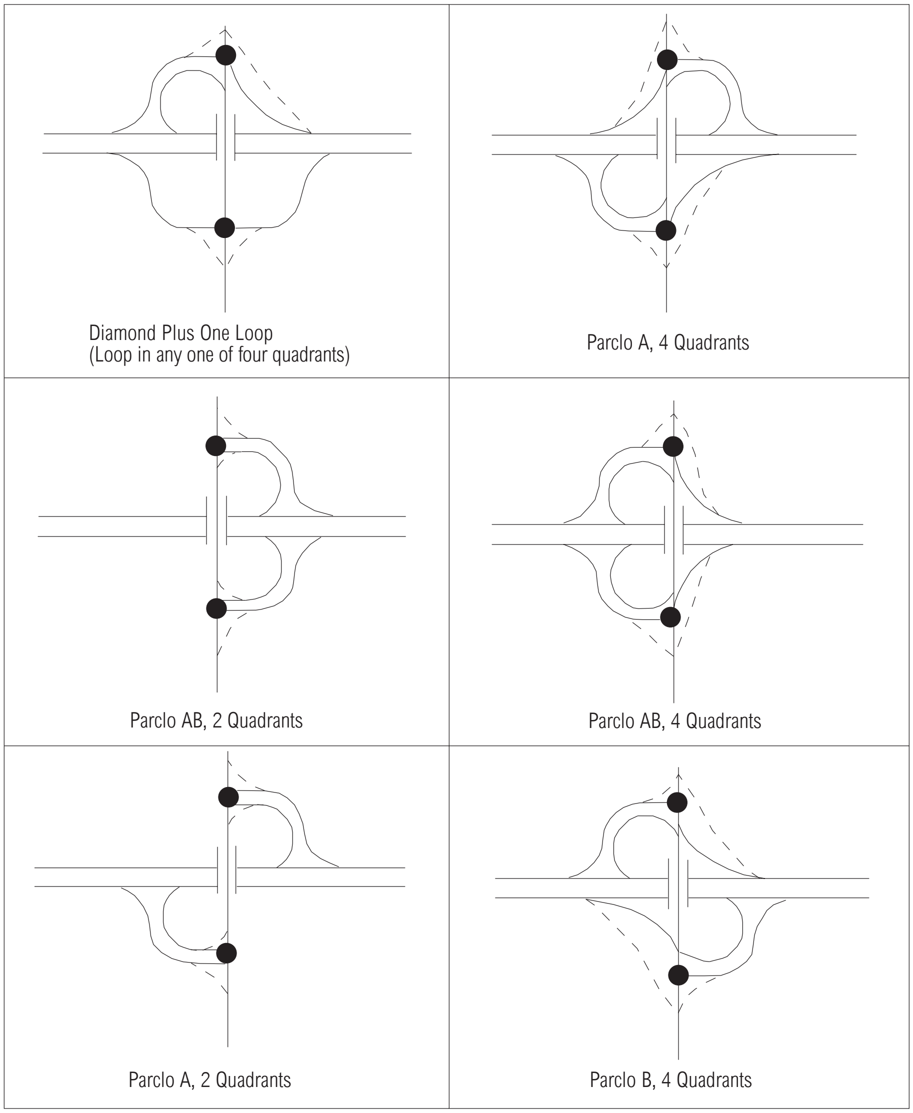
Three-level diamond interchange



Single-point diamond interchange

Note:
Schematic, not to scale.
– – – – Possible configuration of signal bypasses operating as unsignalized movements

EXHIBIT 26-2. TYPES OF CLOVERLEAF INTERCHANGES



Diamond Plus One Loop
(Loop in any one of four quadrants)

Parclo A, 4 Quadrants

Parclo AB, 2 Quadrants

Parclo AB, 4 Quadrants

Parclo A, 2 Quadrants

Parclo B, 4 Quadrants

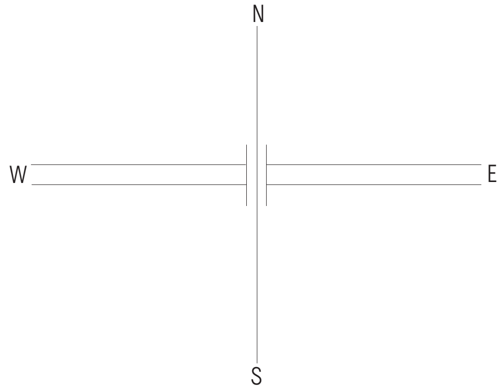
– – – – – Possible configuration of signal bypasses operating as unsignalized movements

Influence of Interchange Type on Turning Movements

The type of interchange has a major influence on turning movements. Movements that involve a right-side merge in one configuration become left turns in another. Movements approaching the interchange on the surface facility are also affected by the interchange type, depending on whether the ramp movements involve left or right turns. Lane-changing and weaving movements also are affected.

Exhibit 26-3 shows the impact of interchange type on turning movements. The eight basic movements between the freeway or major highway and the surface facility are listed. The exhibit indicates whether the movement is a merge (M), diverge (D), or turning (T) movement at the surface facility terminal, and whether the movement involves a right-side (R) or left-side (L) maneuver.

EXHIBIT 26-3. EFFECTS OF INTERCHANGE TYPE ON TURNING MOVEMENTS



Type of Movement Required for:

Type of Interchange	From Surface Street				From Freeway/Highway			
	S-E	S-W	N-W	N-E	E-N	E-S	W-N	W-S
Diamond	TR[a]	TL	TR[a]	TL	TR[b]	TL	TL	TR[b]
Split Diamond	TR[a]	TL	TR[a]	TL	TR[b]	TL	TL	TR[b]
Parclo A - 4 Quad	DR	DR	DR	DR	TR[b]	TL	TL	TR[b]
Parclo A - 2 Quad	TL	TR[a]	TL	TR[a]	TR[b]	TL	TL	TR[b]
Parclo B - 4 Quad	TR[a]	TL	TR[a]	TL	MR	MR	MR	MR
Parclo B - 2 Quad	TR[a]	TL	TR[a]	TL	TL	TR[b]	TR[b]	TL
Parclo AB - 4 Quad[c]	DR	TL	TR	DR	MR	MR	TL	TR[b]
Parclo AB - 2 Quad[c]	TR[a]	DR	TL	TL	TR[b]	TL	MR	TL

Notes:
Assumes freeway movements are eastbound and westbound. Movement types are with respect to surface street. Merges and diverges may be with or without conflicting flows.
T = turn against conflicting flow   R = right-side movement
M = merge with traffic   L = left-side movement
D = diverge from traffic
a. Could be diverge.
b. Could be merge.
c. Movements are correct only if loop ramps are on east side.

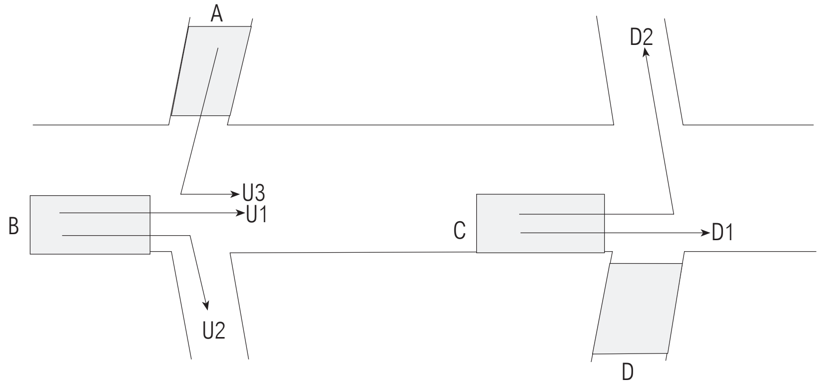
In selecting an appropriate type of interchange, the impacts on the turning movements should be considered. Left-turning movements are always the most difficult in terms of efficiency of operation, and high-volume left-turning movements should be avoided, if possible. By selecting a type of interchange that requires left turns only of minor movements, the overall operation can be enhanced considerably. However, it is not always possible to accomplish this. Right-of-way limitations may preclude the use of loop ramps, and economic and environmental constraints may make multilevel structures undesirable. In the final analysis, a diamond configuration may be required even though it generates heavy left-turn volumes.

UNIQUE OPERATIONS AT SIGNALIZED DIAMOND INTERCHANGES

The signalized diamond interchange presents several unique situations for analysis. In effect, the diamond interchange configuration—except for that of the single-point diamond—places two signalized intersections in proximity, with heavier-than-usual left-turning and right-turning movements as vehicles enter and exit the freeway or major highway. The two intersections do not operate in isolation—each affects the other in ways that are unique to the configuration. Some of these effects, however, also may occur at other signalized intersections that are closely spaced and that have a large amount of left-turn movements. Two-quadrant parclos, for example, typically encounter the same types of problems because their three-phase signalization is similar to that of diamond interchanges. These concepts, therefore, also can apply to similar noninterchange situations in which closely spaced signalized intersections—including closely spaced intersections adjacent to interchange ramp terminals—interact.

Exhibit 26-4 shows a typical signalized diamond interchange. For simplicity, the drawing focuses on one direction of the surface street. Similar impacts occur in the other direction.

EXHIBIT 26-4. TYPICAL SIGNALIZED DIAMOND INTERCHANGE



Each of the signalized intersections of the diamond interchange (in the subject direction) consists of two approaches, labeled A and B for the upstream intersection, and C and D for the downstream intersection. The downstream intersection is fed by movements U1 and U3 of the upstream intersection. Exiting freeway traffic forms a stream that is movement U3 at the upstream intersection and part of movement D1 at the downstream intersection. Entering freeway traffic is part of movement U1 at the upstream intersection, and all of movement D2 at the downstream intersection. The interaction of these movements creates special problems at signalized diamond interchanges.

Queuing Characteristics

The most critical features of a signalized diamond interchange, therefore, are the interdependency of movements and the distance between intersections, both of which influence queuing. The distance separating the intersections limits the amount of queuing that can occur downstream without blocking the upstream intersection. The extent of queuing at the downstream intersection depends on several factors, including the timing at the upstream and downstream signals, the number and use of the lanes at both intersections, and the flow rates in the movements (U1 and U3) that feed the downstream intersection.

Impacts from downstream queuing

Queuing from the downstream intersection can have one of the following three impacts on the discharge from the upstream intersection:

1. Conditions at the downstream intersection are not severe enough to affect the upstream intersection.
2. Queuing from the downstream intersection does not completely block the upstream discharge but reduces its rate due to the proximity of the back of the queue.
3. Queuing from the downstream intersection effectively blocks the discharge from the upstream signal during portions of its green period.

Queued vehicles within a short segment (or link) limit the effective length of the link. Vehicles can travel freely only from the upstream stop line to the back of the downstream queue. Because this distance may be small, the impact on upstream discharge rate is significant.

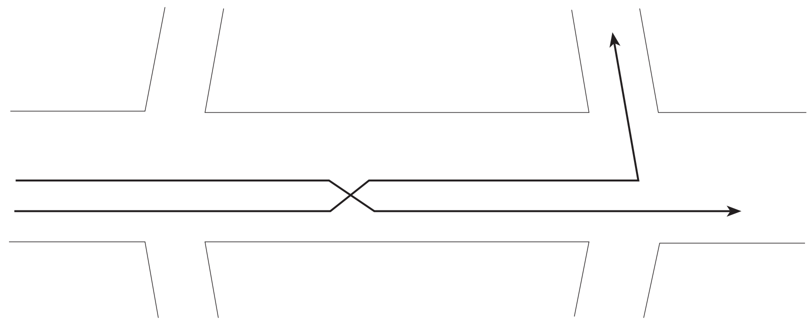
Complicating the situation is that this process is iterative. Downstream queues affect upstream discharges; upstream discharges affect downstream queues by metering the number of vehicles that can enter the short link between the diamond intersections. This complex relationship has not been fully studied and documented; therefore, the material in this chapter is conceptual and is not based on a definitive model for signalized diamond interchange operations.

Lane Change Movements

Internal links

Because of the turning movements at diamond interchanges, the internal link of the surface street (the link between the two signalized diamond intersections) is subject to abnormally high numbers of lane-changing maneuvers. Exhibit 26-5 depicts this phenomenon.

EXHIBIT 26-5. LANE CHANGE MOVEMENTS AT A DIAMOND INTERCHANGE



The lane changes occur because of origin-destination patterns. The turbulence of the lane changing can decrease the normal link speed. In addition, if there is queuing on the link, it reduces the effective weaving or lane-changing distance, increasing the turbulence and its potential effects on the traffic. In many cases, drivers try to pre-position themselves in the appropriate upstream lane, and left turns from the surface street can enter a turn bay at the entry point on the internal link. This tends to minimize lane-changing turbulence.

Lane Utilization

Because of the potential for heavy turning flows at signalized diamond interchanges, lane utilization may differ from that at other signalized intersections. At the downstream intersection, heavy left-turning and through flows normally will segregate, and lane-use regulations generally encourage maximum segregation. While this might occur at any signalized intersection with turning flows, the difference is in the impact on the upstream intersection. Because the internal link generally is short, segregation may occur at the upstream intersection by driver selection or by designated signing and striping. Thus, the upstream approach flow can be segregated substantially into two flows, both of which are through flows at the upstream intersection: one will turn left at the downstream intersection, and one will continue through it. This can create lane-use imbalances that exceed those at normal intersections but that must be taken into account by creating separate lane groups for through vehicles at the upstream intersection.

Platoon Behavior

Because of the high volume of turns at a diamond interchange, it is difficult to maintain platoons as vehicles pass through the two intersections. It is also difficult to maintain the signal progression through the interchange. Platooned arrivals at the downstream intersection come from two sources: left turns from an interchange ramp, and through movements from the surface street. The ramp may contribute a higher volume than the surface street and therefore would be the primary candidate for progressed movement. In any case, the two sources arrive from two different signal phases. No matter what signalization is adopted, one of the movements will be disadvantaged. Some portion of the lesser movement will arrive at the downstream intersection during a red period, and the queued vehicles then will alter the platoon structure that proceeds down the surface link.

Although heavy turning movements from the interchange ramps add vehicles to platoons on the surface link, heavy left-turning movements of vehicles onto the freeway or major highway remove significant numbers of vehicles, creating gaps in the platoons.

Demand Starvation

Demand starvation occurs when portions of the green at the downstream intersection are not used because conditions prevent vehicles at the upstream intersection from reaching the downstream stop line. These conditions at the upstream intersection can include delays or blockage due to queue overflow from another lane group. Demand starvation occurs in one of two ways:

1. Queues from the downstream intersection effectively block departures from the upstream intersection during part or all of the upstream green. This reduces the effective green time for flow at the upstream location during the green time at the downstream intersection.
2. Signal coordination between the two intersections is suboptimal even without downstream queuing. As a result, sometimes the upstream signal is red while unsaturated flow conditions prevail during the green at the downstream signal.

Signal Phasing and Timing Strategies

Appendix A provides more information about the signalization of diamond interchanges

Because of the unique operational characteristics of signalized diamond interchanges, special signal phase plans and timing often are appropriate. Appendix A covers the signalization of diamond interchanges in greater detail. *Capacity of Interchange Ramp Terminals* (*1*) describes a range of interchange signalization practices. The key point is that interchange performance is closely linked to signal timing, due to the interdependence of flows, queuing, and timing.

II. METHODOLOGY

Because this chapter outlines only a conceptual approach for analyzing signalized diamond interchanges, it does not present a detailed analytic methodology with applications. The conceptual methodology has two primary components:

- A level-of-service (LOS) framework, and
- A framework for estimating saturation flow rates.

LOS FRAMEWORK

The recommended framework for LOS is to treat the diamond interchange as a point rather than as a segment or system, and to focus on the total control delay experienced by drivers as they move through the interchange.

Exhibit 26-6 shows the various movements at the diamond interchange. In the exhibit, movements are labeled as coming from the west intersection (W) or the east intersection (E). An r designation indicates that the movement originates from one of the ramps. The next two letters indicate whether the movement is a left turn (L), a right turn (R), or a through movement (T) first at the upstream intersection and then at the downstream intersection, if both intersections are traversed. For example, the designation WrLT means a left turn from the west intersection ramp proceeding straight through the east intersection.

EXHIBIT 26-6. MOVEMENTS IN A DIAMOND INTERCHANGE

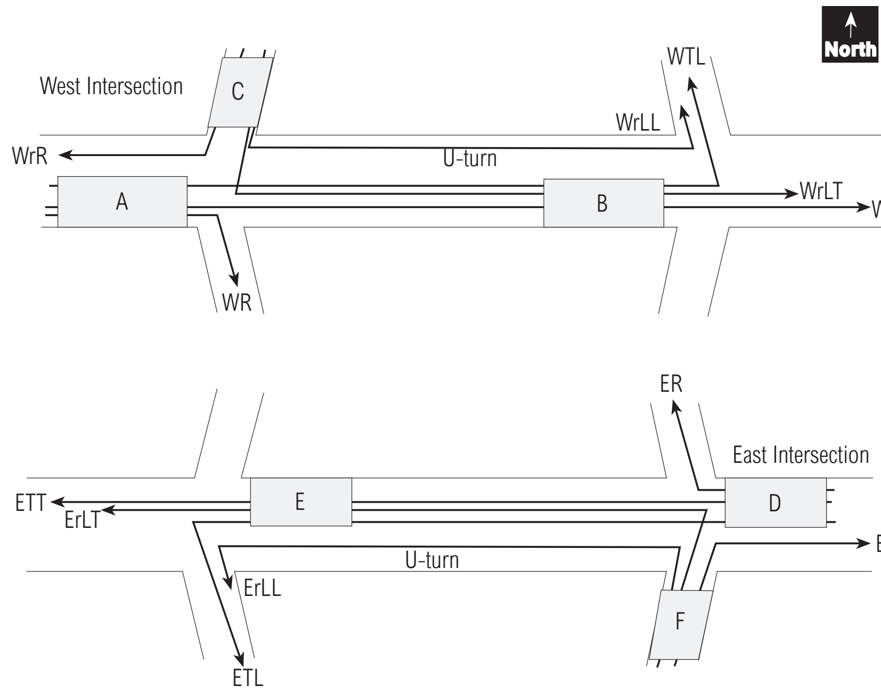


Exhibit 26-7 indicates the components of delay that must be included in the LOS analysis of each movement. Each movement experiences the delay of each lane group it uses while passing through the interchange. Since the diamond interchange is being considered as a point, the recommended LOS framework does not account for the travel time between the two diamond intersections.

EXHIBIT 26-7. COMPONENTS OF INTERCHANGE DELAY

Movement	Control Delay from Lane Groups of Approach[a]
WTL	A and B
WTT	A and B
WR	A only
WrR	C only
WrLT	C and B
WrLL	C and B
ETL	D and E
ETT	D and E
ER	D only
ErR	F only
ErLT	F and E
ErLL	F and E

Note:
a. See Exhibit 26-6 for approach designations.

The control delay for each of the approach lane groups can be estimated using the signalized and unsignalized intersection methodologies of Chapters 16 and 17, taking into account progressive flows by estimating an appropriate arrival type. Unsignalized yield and free-flow movements are to be included in the analysis, because performance differences between alternate interchange forms can be seen only by considering all ramp terminal movements. For instance, the benefits of free-flow movements may be hidden unless delays and volumes of all movements are incorporated, as shown in the example in Appendix B.

LOS for the individual groups is then determined from Exhibit 26-8, which uses LOS criteria for signalized intersections described in Chapter 16. If any lane group performs poorly—that is, if it falls in the LOS E or F range—the impact on the rest of the interchange likely will not be identified unless queuing is analyzed in greater detail. If there is severe queuing or upstream blockage, timing or design changes should be considered, regardless of the LOS. In all cases, spillback onto the mainline freeway should be avoided because of the potential for high-speed rear-end accidents. To reduce ramp queuing, the timing may be adjusted so that the surface street approaches, rather than the exit ramp approaches, perform at LOS F.

EXHIBIT 26-8. LOS CRITERIA FOR INTERCHANGES

Level of Service	Delay (s/veh)
A	≤ 10
B	> 10–20
C	> 20–35
D	> 35–55
E	> 55–80
F	> 80

A comprehensive analysis would consider the interaction of flows, queues, and signal timing. The LOS analysis could be based on complete movements through the interchange, as defined in Exhibits 26-6 and 26-7. Such a procedure may be presented in future editions of this manual.

Finally, a combined average control delay per vehicle for the interchange is computed:

$$d_{INT} = \frac{\Sigma(d_i v_i)_{A-F}}{\Sigma(v_i)_{A-F}} \qquad (26\text{-}1)$$

where

d_{INT} = average control delay per vehicle for the interchange (s/veh),

d_i = average control delay for Lane Group i on Approaches A–F (s/veh), and

v_i = demand flow rate for Lane Group i (veh/h).

The equation includes the delays and the flow rates from all lane groups in A through F. The computed delay therefore is the weighted average intersection delay of the two ramp terminal intersections. LOS is determined using the criteria in Exhibit 26-8.

SATURATION FLOW RATES FOR INTERCHANGE LANE GROUPS

The estimation of saturation flow rates at signalized intersections within a diamond or other interchange generally follows the procedures of Chapter 16. However, there are necessary modifications for the unique interactions that occur in closely spaced, signalized intersections with high turning volumes. Currently, there are no fully developed and evaluated methodologies for making these modifications, although some have been proposed and are under study.

III. APPLICATIONS

Without a complete methodology, specific applications cannot be discussed or illustrated. However, the methodologies of Chapters 16 and 17 can be applied as a rough approximation, as presented above, and the LOS criteria listed in Exhibit 26-8 then can be used to estimate LOS.

Nonetheless, such an application does not take into account all of the unique operating conditions that affect operations at interchanges. Exhibit 26-9 lists the principal components of the framework for a complete interchange analysis.

EXHIBIT 26-9. FRAMEWORK FOR COMPREHENSIVE INTERCHANGE RAMP TERMINAL ANALYSIS

Inputs
• Traffic characteristics, • Geometrics, and • Control characteristics.
Signalized Movement Analysis
• Generally follow Chapter 16; • Modify to include - Appropriate lane group definition, including pre-positioning, - Blockage by downstream queues, - Proximity to downstream queues (reduced speed), - Traffic pressure and interchange site effects, - Left- and right-turn radius effects, and - Demand starvation, and • Analyze resulting capacity, queuing, delay, and LOS.
Weaving and Merge Movements
• Consider operational effects (no procedure defined in HCM) and • Analyze capacity, queuing, delay, and LOS.
Unsignalized Movements
• Apply Chapter 17 methodology and • Analyze resulting capacity, queuing, delay, and LOS.
Evaluation
• Measure performance (including queuing effects) of approach lane groups and movements through the interchange; • Perform an iterative analysis, to account for queue interactions; • Determine average performance of interchange; • Determine overall LOS of interchange; and • Analyze short interchange area segments comprising three to four closely spaced intersections.

When determining the LOS for diamond interchanges, the analyst should identify several components integral to operational analysis, including, but not limited to

- Interchange geometry, including the number of lanes and storage;
- Lane use and utilization;
- Peak-hour turning volumes; and
- Anticipated signal phasing and cycle lengths.

The first step is to determine the current or projected queuing by lane group and by traffic signal phase. If the queuing between traffic signals is due to the signal phasing and if this is causing backups that cannot be stored, then alternative signal phasing should be identified so that the interchange may operate more efficiently within its geometric limitations. However, the ramifications of this new signal phasing must be explored to determine its impact on the operational efficiency of the interchange.

An example of analyzing phasing would be to determine if the traffic queuing and storage for three-phase operation at a diamond interchange will function without causing queue spillback and additional traffic delays. If three-phase operation causes queue spillback and is inefficient, then changing to four-phase operation may be necessary. Four-phase signal timing basically allows each of the four approaches to the interchange to operate on a separate phase. There are many different ways to achieve four-phase operation, by changing phase order and by sequencing signal overlaps. Three-phase operation allows two directions of travel to move concurrently most of the time, but four-phase operation requires that three phases wait while one is served. Changing from three-phase to four-phase operation at a diamond interchange normally creates a significant adverse impact on delays and LOS.

There are many other phasing sequences and offset relationships to consider. Variations on the basic sequence should stem from the interchange configuration, the ability to store queues, system coordination elements, and the location of queue storage. The selection of leading or lagging (or both) left-turn arrows and overlap phasing may be necessary, as well as choice of protected, permissive, or protected-and-permissive left-turn phasing. Actuated operation is another factor. Appendix A presents signal timing considerations for signalized diamond interchanges; more discussion on this complex topic can be found in other references (*1*, *2*).

IV. EXAMPLE PROBLEMS

Example problems are omitted from this chapter because a complete methodology is not specified. However, Appendix B presents a numerical exercise illustrating the simplified approach described earlier.

V. REFERENCES

1 Messer, C. J., and J. A. Bonneson. *Capacity of Interchange Ramp Terminals*. Final Report NCHRP Project 3-47. Texas A&M Research Foundations, College Station, April 1997.
2. Akcelik, R. *Interchange Capacity and Performance Model for HCM 2000*. Technical Note, ARRB Transport Research Ltd., Vermont South, Australia, October 1998.

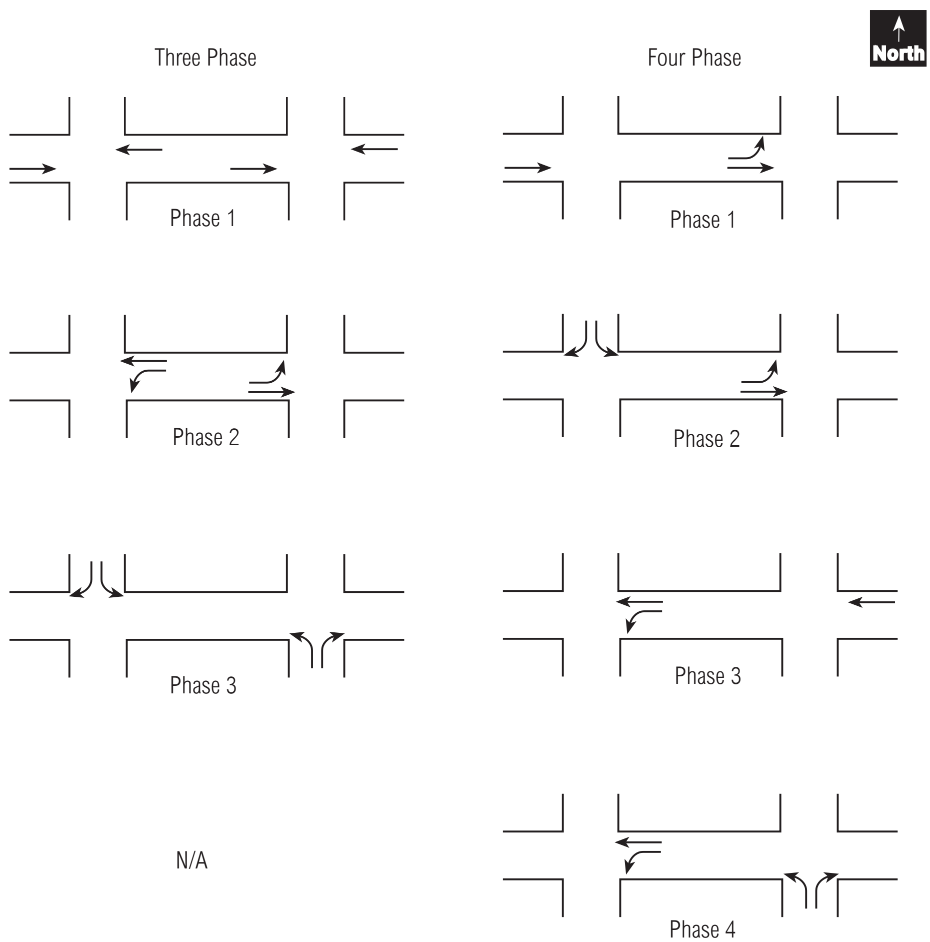
APPENDIX A. TIMING CONSIDERATIONS FOR SIGNALIZED DIAMOND INTERCHANGES

The signalization of two closely spaced intersections with heavy turning movements, as in a signalized diamond interchange, presents several major challenges. Most of these involve the queuing of vehicles between the two intersections on the inside link, affecting operations as described in this chapter. In addition, virtually every signalized diamond interchange involves heavy left-turning movements, necessitating multiphase signalization at both intersections and making progression and platoon cohesion along the surface street difficult to maintain.

PHASING OPTIONS

Signalized diamond interchanges usually employ integrated phasing—that is, they use a single, often semiactuated controller for both intersections. Although there are several subalternates, the basic decision is whether to use a three-phase or a four-phase system. The three-phase system provides a more efficient use of time, but can lead to queuing problems on the inside link. The four-phase system is less efficient in use of time but avoids most queuing problems. Both are illustrated in Exhibit A26-1.

EXHIBIT A26-1. COMMON SIGNALIZATION SCHEMES FOR DIAMOND INTERCHANGES



The basic three-phase scheme features a phase for through movements on the surface street, a phase for movements from all inside links, and a phase for ramp movements. As an alternative, Phases 2 and 3 can be switched.

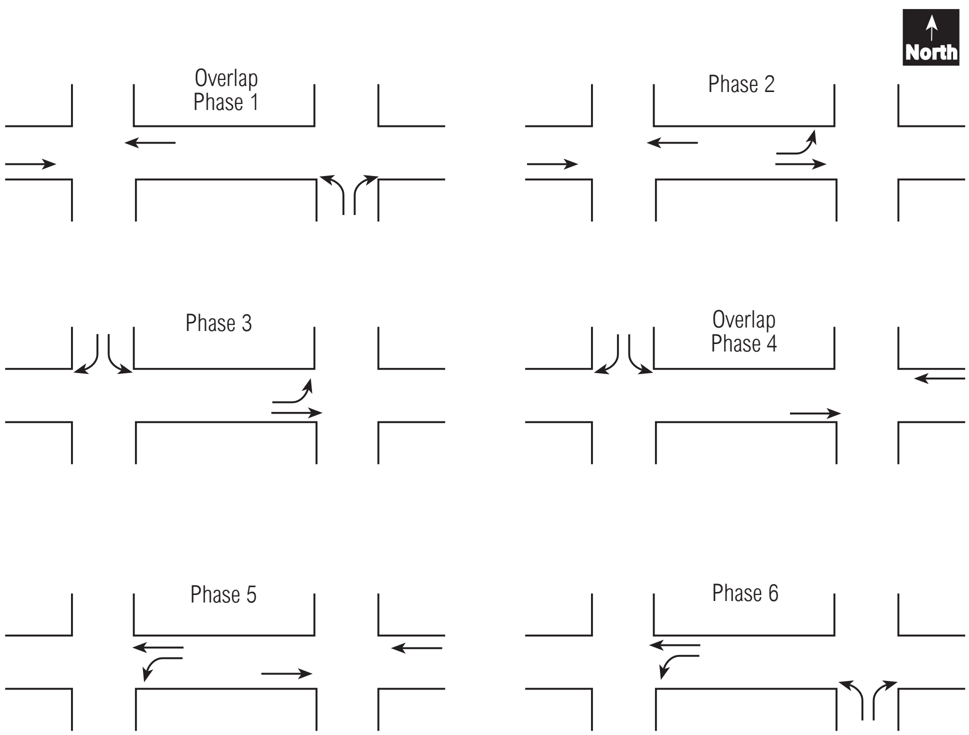
The primary problem occurs in Phase 3. Left-turning vehicles from both ramps are entering the inside link and begin to queue at the downstream signal during the phase, which is now red. If queuing can cause a problem, this scheme should be avoided. The number of vehicles that will accumulate on the inside link can be estimated by taking the effective green time for Phase 3 and applying an estimated discharge rate for left-turning vehicles for each ramp. Given the number of lanes and the length of the inside link, the general impact of queued vehicles (in each direction) can be assessed.

Note that in the three-phase sequence of Exhibit A26-1, Phase 1 follows Phase 3 and introduces another set of vehicles into the inside link. If Phases 2 and 3 are switched, a phase discharging the inside link would follow and should help to reduce the impact of the queues.

If it is clear that queuing on the inside link will be a regularly occurring problem in the three-phase configuration, the four-phase option is a better choice. Each of the four approaches from which interchange traffic originates is given a clear phase through both intersections. Queuing is minimized because vehicles are stopped from entering the inside link at the same time that vehicles are stopped from leaving it. Although it constrains the negative impacts of queuing, a four-phase plan generally decreases the effective green time per cycle (g/C) ratio for major movements, so that expected delays are higher than for a three-phase plan—assuming in both cases that there are no flow breakdowns due to queuing.

Exhibit A26-2 shows a four-phase plan with overlaps that is more efficient than the simple four-phase plan. In Overlap Phases 1 and 4 of this plan, an opposing through vehicle is allowed to enter the inside link during a phase in which it cannot exit the link. The timing of these overlap phases is critical to proper operation and is related to the ideal offset between the two diamond intersections. The initiation of Phase 2 with respect to Phase 1 should be the ideal offset on the inside link in the eastbound direction, while the initiation of Phase 5 with respect to Phase 4 should be the ideal offset on the inside link in the westbound direction.

EXHIBIT A26-2. FOUR-PHASE PLAN WITH OVERLAP



ESTABLISHING OFFSETS

An offset is the difference, in seconds, between the start of green time at the two signalized intersections of a diamond interchange; it is used to coordinate the through traffic passing through the internal link. Both intersections in either the basic three-phase or four-phase signalization are commonly timed from a single controller. The signal phases and overlaps installed in the timing pattern can be established to allow traffic to move through the interchange, reducing the probability of stopping. The two intersections sometimes are timed by separate controllers and linked together; the offsets then should be established to minimize unnecessary stopping.

Optimizing offsets

When the through traffic on the surface street is a dominant feature and the ramp flows are no larger than the normal turning volumes at other intersections, the standard ideal offset may be used; this offset is equal to the travel time from the upstream to the downstream stop line at the average running speed of traffic.

$$\theta_{ij} = \frac{L}{S} \quad \text{(A26-1)}$$

where

- θ_{ij} = offset for through movements at Intersections i and j, between the start of the downstream through green and the upstream green (s);
- L = length of the link (i-j) from the upstream stop line to the downstream stop line (m); and
- S = average running speed on the surface street (m/s).

Normally, however, ramp movements are significant enough to create queuing on the inside link. In such cases, the ideal offset should be based on clearing the queue at the downstream intersection:

$$\theta_{ij} = \frac{L}{S} - \frac{(1-P)*v*C}{s} \quad \text{(A26-2)}$$

where

- P = proportion of vehicles arriving on green,
- v = arrival flow rate at the downstream intersection (veh/h),
- C = cycle length (s), and
- s = saturation flow rate at the downstream intersection (veh/h).

A third guideline for optimizing offsets is also available (*1*). This criterion is based on minimizing demand starvation and is related to the maximum storage on the inside link. To minimize demand starvation, the offset should be greater than or equal to the computation produced by Equation A26-3.

$$\theta_{ij} = \frac{L}{S} - \frac{3{,}600 * N * L}{s * l} \quad \text{(A26-3)}$$

where

- N = number of lanes on link i-j, and
- l = queue storage length per vehicle (m).

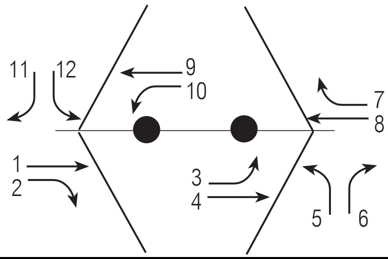
In general, the selection of an offset must consider many factors, including the flow level, the traffic pattern, and the degree of saturation at the downstream signal. However, to enhance the throughput efficiency during high-volume conditions, the offset should be greater than or equal to the larger value produced by Equations A26-2 and A26-3.

Ideal offsets often can be provided only in a single direction. Once an ideal offset is established in one direction, the offset in the other is often already determined. Although multiphase operation at most interchange signals can provide some flexibility, other signal timing requirements can dictate the opposing offset. In such cases, it is necessary to consider both offsets and to determine a plan that is most effective for the overall operation of the interchange, even though neither offset may be ideal.

APPENDIX B. ASSESSMENT OF ALTERNATIVE INTERCHANGE CONFIGURATIONS

Assessment Three alternative configurations are presented for an interchange. Volumes (veh/h) and control delay (s/veh) are given for each movement. Control delay and overall LOS are determined to compare the alternatives and to illustrate the effect of including all interchange movements in the calculations.

Alternative 1. Diamond, no free-flow movements or right turn on red (RTOR)

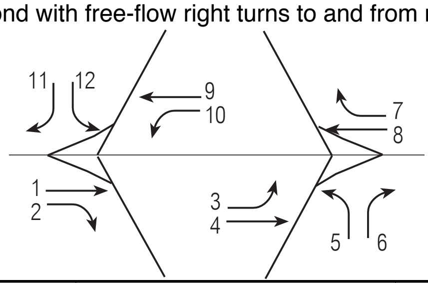


Movement No.	Volume (veh/h)	Delay (s/veh)
1	800	30
2	300	30
3	300	20
4	800	35
5	200	50
6	400	50
7	400	40
8	900	40
9	700	45
10	400	25
11	300	45
12	300	45

Calculations

- Total interchange delay (all 12 movements), 217,500 veh-s;
- Total interchange volume (all 12 movements), 5,800 veh/h; and
- Average interchange control delay = $\frac{217{,}500}{5{,}800} = 37.5$ s/veh (LOS D).

Alternative 2. Diamond with free-flow right turns to and from ramps

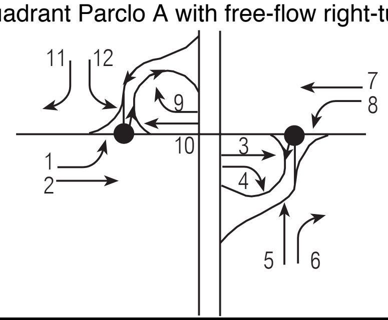


Movement No.	Volume (veh/h)	Delay (s/veh)
1	800	30
2	300	0
3	300	20
4	800	35
5	200	50
6	400	0
7	400	0
8	900	40
9	700	45
10	400	25
11	300	0
12	300	45

Calculations

- Total interchange delay (all 12 movements), 159,000 veh-s;
- Total interchange volume (all 12 movements), 5,800 veh/h;
- Total volume (excluding free-flow movements), 4,400 veh/h;
- Average interchange control delay (all volumes) = $\frac{159,000}{5,800}$ = 27.4 s/veh (LOS C), and
- Average interchange control delay (excluding free-flow volumes) = $\frac{159,000}{4,400}$ = 36.1 s/veh (LOS D).

Alternative 3. Two-quadrant Parclo A with free-flow right-turn exit ramps



Movement No.	Volume (veh/h)	Delay (s/veh)
1	300	30
2	800	30
3	800	35
4	300	0
5	200	50
6	400	0
7	900	40
8	400	40
9	400	0
10	700	45
11	300	0
12	300	45

Calculations

- Total interchange delay, 168,000 veh-s;
- Total interchange volume, 5,800 veh/h;
- Total volume (excluding free-flow movements), 4,400 veh/h;
- Average interchange control delay (all volumes) = $\frac{168,000}{5,800}$ = 29.0 s/veh (LOS C); and
- Average interchange control delay (excluding free-flow volumes) = $\frac{168,000}{4,400}$ = 38.2 s/veh (LOS D).

Results The summary of results follows.

Alternative	Delay/LOS	
	Using all Volumes	Excluding Free-Flow Volumes
Diamond, no free-flow movements or RTOR	37.5/D	37.5/D (no change)
Diamond, with free-flow right turns to/from ramps	27.4/C	36.1/D
Two-quadrant Parclo A, with free-flow right-turn exit ramps	29.0/C	38.2/D

Considering all interchange volumes, the last two alternatives, which include free-flow movements, outperform Alternative 1 by one service level. They perform about the same for the given conditions. If free-flow volumes had been excluded, however, the benefits of this design feature would have been masked—the average delay and LOS of all three alternatives would be the same, as shown on the right side of the results summary.