COORDINATION OF DIAMOND INTERCHANGES WITH ADJACENT TRAFFIC SIGNALS

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16. Abstract

This report contains the documentation of research conducted by the Texas Transportation Institute (TTI) during a two-year project funded by the Texas Department of Transportation. The primary objective of this project was to develop guidelines for coordinating diamond interchanges with adjacent traffic signals on the arterial. The report begins with a presentation of the current status of technology and state-of-practice for timing diamond interchanges in Texas. In addition, the report provides a detailed analysis of various control strategies. The report describes a new methodology for estimating the capacity of interchanges and provides guidelines for coordinating an interchange with adjacent traffic signals. Finally, the report presents the results of two field studies conducted by researchers to evaluate the methods developed in this project.

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1. INTRODUCTION

BACKGROUND

Diamond interchanges serve as critical links between roadway facilities of two different classifications: freeways and surface street systems. Thus, the operation of a diamond interchange can affect or be affected by the location, design, and operation of adjacent traffic signals and ramps. Especially during peak traffic conditions, inefficient operation of a diamond interchange and adjacent traffic signals may cause either system to become a bottleneck, downgrading not just the capacity of the interchange but also that of the arterial and, in some cases, even the capacity of the freeway ramps. In many cases, the already complex nature of traffic flow through a diamond-interchange and adjacent traffic-signal system is further complicated by weaving and queuing caused by traffic movements to and from offices, shopping malls, and gas stations located in the vicinity of the interchange.

Many TxDOT districts and Texas cities face similar operational problems within diamond interchange environments on a daily basis. Although it is recognized that these complex operational problems can be solved only through optimal design and operation of diamond interchanges and adjacent traffic signals as interdependent systems, no user-friendly guidelines or optimization/analysis tools are currently available to TxDOT and local agencies in achieving this objective. TxDOT initiated this two-year project to fill the existing gap in technologies for analyzing and optimizing the flow of traffic in congested diamond interchange environments and for developing guidelines to coordinate diamond interchanges with adjacent traffic signals on the arterial. Researchers identified the following specific needs:

- Define the interdependencies that exist between interchanges and adjacent traffic signals.
- Investigate conflicts and transitions and establish priorities for traffic flow.
- Identify problems (weaving, queuing, spillback, etc.) and their roots in relationships to the interchange environment geometry (design) and traffic flow distribution.
- Develop user-friendly guidelines and solutions techniques that can be applied to the full range of situations encountered by TxDOT and other operating agencies.
- Conduct field studies to demonstrate the applicability of guidelines and procedures developed.

Another issue, the need for multi-jurisdictional cooperation, surfaces when two agencies are responsible for maintaining various subsystems in a given environment. For diamond interchange environments in Texas, the following three possible scenarios generally exist:

- TxDOT maintains a diamond interchange and adjacent signals on the arterial.
- A city maintains an interchange and adjacent signals.
- TxDOT maintains the diamond and a city maintains all adjacent signals.

The first two cases are relatively simple to deal with, whereas the third is usually more difficult from a logistics point of view. Furthermore, in the last case, control objective and movement priorities may be perceived differently by the two agencies, resulting in non-optimal control.

Regardless of the maintenance arrangement, drivers expect their movement through an interchange environment to be as smooth as possible. Thus, there is also a need to ensure that the guidelines and procedures developed in this project are sensitive to these issues.

RESEARCH OBJECTIVES

The primary objective of research described in this report was to develop procedures and guidelines for mitigating arterial congestion at diamond interchanges and adjacent traffic signals, especially those located in densely developed urban areas. The specific objectives were to:

1. develop user-friendly procedures for coordinating diamond interchanges with adjacent traffic signals,
2. develop guidelines for effectively using the research results, and
3. test the developed guidelines using field studies.

SCOPE

The scope of this two-year project was limited to diamond interchanges with one-way frontage roads and the coordination of these interchanges with adjacent signals on the arterial during congested traffic conditions.

RESEARCH APPROACH

The approach used in this research project included several systematic steps. These included:

1. understanding the problems and identifying TxDOT and city priorities,
2. defining traffic control objectives,
3. developing analytical procedures for analyzing and optimizing signal timings,
4. testing the developed procedures using computer simulation, and
5. testing the usefulness of developed procedures using field studies.

ORGANIZATION OF THIS REPORT

This report consists of six chapters. Chapter 2 presents an overview of existing technology for the analysis and optimization of diamond interchanges and their coordination with adjacent traffic signals on the arterial. Chapter 3 provides the results of a survey we conducted to better understand current state-of-practice in Texas, and to help define TxDOT priorities and objectives for diamond interchange control. Chapter 4 provides a detailed analysis of various diamond interchange control strategies used in Texas. This chapter also describes a methodology for analyzing the capacity of a diamond interchange. Chapter 5 discusses coordination of diamond interchanges with adjacent traffic signals and presents a simple methodology to coordinate a diamond interchange with an adjacent traffic signal. In addition, this chapter addresses traffic congestion and describes an advanced procedure for timing a diamond interchange and adjacent traffic on the arterial. Finally, Chapter 6 presents the results of the application of methods, described in previous chapters, to two sites in Texas.

2. CURRENT STATE OF TECHNOLOGY

This chapter begins with a description of diamond interchanges, followed by an overview of Texas diamond control strategies. Then, we present the results of a survey we conducted to understand current Texas practice of timing diamond interchanges and to understand the priorities and objectives of diamond interchange control.

DESCRIPTION OF DIAMOND INTERCHANGES

There are two general classes of interchanges. System interchanges provide connections between freeways and are characterized by free flow transitions. Service interchanges, on the other hand, provide transitions between facilities of different functional classification. Single-point, partial cloverleaf, three-level diamond, and conventional diamond are examples of service interchanges. The traffic flow at these interchanges is characterized by heavy turning movements and large variations in vehicular speeds, including acceleration and deceleration.

There are several variations of diamond interchanges; however, diamond interchanges with one-way frontage roads are the most prevalent type of service interchanges in Texas. Figure 1 illustrates the links between the most common form of diamond interchange in Texas with other roadway elements: frontage roads, exit ramps, on-ramps, and signals on the local street/arterial.

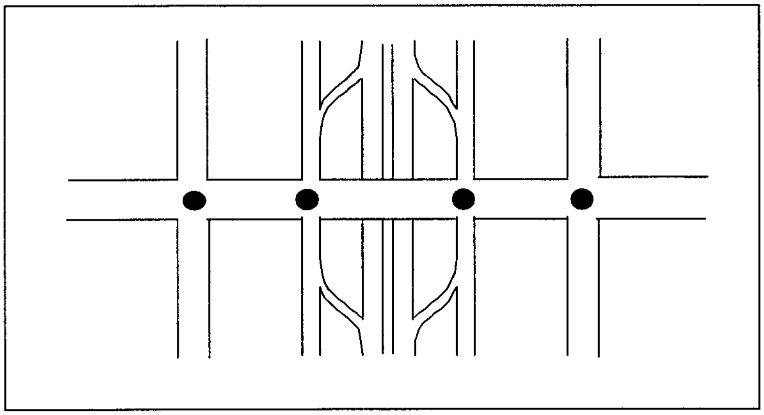


Figure 1. A Typical Diamond Interchange Environment.

A diamond interchange consists of two intersections. Depending on the distance between these two intersections, diamond interchanges are further classified into three types described below:

1. A conventional diamond interchange is one in which the distance between the two intersections is more than 800 ft (244 m). These interchanges are located in rural settings and are generally controlled by stop signs.

2. An interchange is classified as a compressed diamond when the distance between the two intersections is between 400 and 800 ft (122 and 244 m). These intersections are usually found in suburban areas. In most cases, both intersections of the interchange have signal control with or without interconnection.

3. Tight diamond interchanges are characterized by two signals less than 400 ft (122 m) apart. These interchanges are located in highly developed areas and are always signal controlled. Because of the close proximity of the two signals, they are and should be designed and operated as one system.

Unless two-way frontage roads are present, the three forms of diamond interchanges listed above have three approaches to each intersection.

The interdependency of several factors – close proximity of the two intersections of an urban diamond interchange, heavy turning traffic, and speed transitions – present a considerable challenge in selecting strategies for the optimal operation of a diamond interchange and adjacent signal on the arterial. As will be discussed later, there is a lack of guidelines, procedures, and tools for coordinating a diamond interchange with signals on the arterial. This is particularly true for facilities facing congested traffic conditions.

Diamond Interchange Operation

In Texas, most signalized urban diamond interchanges are operated using a single traffic controller using either one of two strategies described in the TxDOT diamond control specifications. In addition to the Texas diamond control mode, most modern signal controllers also provide additional modes for operating a pair of signalized intersections. This section describes various phasing schemes that can be used at diamond interchanges.

Figure 2 shows all traffic movements at a diamond interchange. Each signal of the interchange, when considered in isolation, can be controlled using either two or three phases. The number of phases depends on whether the left-turn movement needs a protected phase or not.

A protected left-turn phase is required when the left-turn demand is high or when there is heavy opposing through traffic. Since this research project deals with the operation of diamond interchanges facing congested or near congested traffic conditions, we consider only the protected left-turn case. Thus, we assume each signal has the following three phases:

- frontage road phase,
- arterial through phase, and
- left-turn phase.

The protected left-turn phase can be displayed before or after the opposing through phase, resulting in two possible phase sequences for the arterial approaches at each intersection of the diamond. These phase patterns are commonly referred to as leading and lagging phases, respectively.

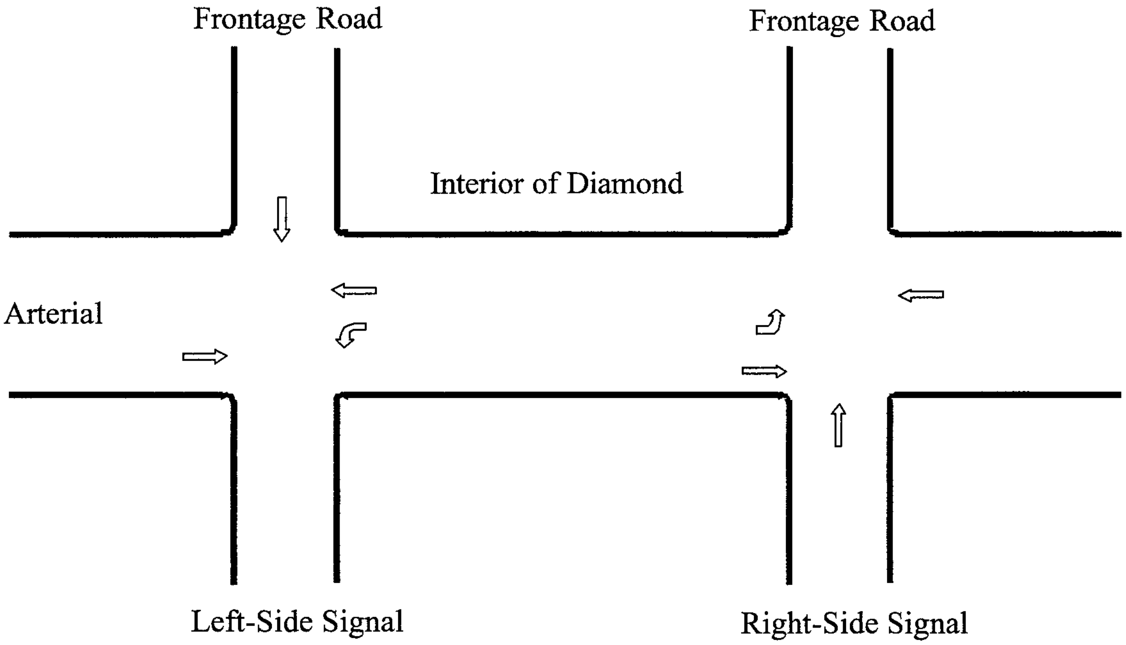


Figure 2. Movements at the Two Intersections of a Diamond Interchange.

In Texas, it is common to operate both intersections of an urban diamond interchange using a single controller. Furthermore, the two intersections of a diamond interchange are referred to as one entity, the interchange. Thus, any reference to signal timing includes not only the joint set of phasing patterns at the two intersections, but also the cycle length and the offset relationship between the two intersections. Combined, the cycle length and the offset establish coordination between the two intersections of a diamond interchange. Regardless of whether the control is pretimed or actuated, the two intersections of the diamond always have the same cycle length, which is a prerequisite for coordination. Combining the phasing patterns for each intersection into one set results in fours phasing patterns for the diamond interchange. These are commonly referred to as:

- lead-lead phasing (leading left-turns at both intersections),
- lead-lag phasing (leading left-turn at the left intersection, and lagging left-turn at the right intersection),
- lag-lead phasing (Lagging left-turn at the left intersection, and leading left-turn at the right intersection), and
- lag-lag phasing (legging left-turns at both intersections).

The standard Texas diamond mode permits only a subset of the above phasing options. Furthermore, left-turn phase sequence and offset between the two signals is implicitly taken care of by selecting one of the standard diamond modes of operation. The following subsections summarize these modes.

Texas Three-Phase Strategy

Figure 3 provides an illustration of the Texas three-phase strategy. This strategy uses lag-lag phasing and is designed to provide arterial through progression. Three-phase control works well as long as there is balanced demand at the two frontage roads/ramps and when there is sufficient storage space between the two intersections (interchange interior). In the next chapter, we will provide more detailed analysis of the three-phase operation.

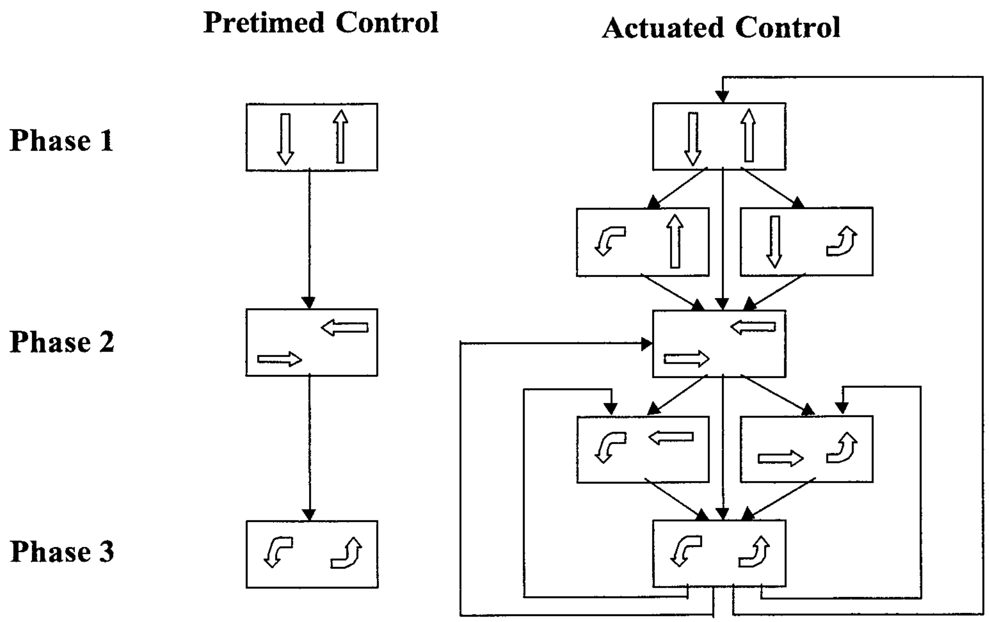


Figure 3. Texas Three-Phase Control Strategy.

Texas Four-Phase Strategy

Figure 4 provides an illustration of the Texas four phase strategy. This strategy is also known as TTI four-phase. TTI four-phase strategy uses lead-lead phasing pattern and minimizes internal queues. The next chapter provides a more detailed analysis of this strategy.

Separate Intersection Mode

Figure 5 illustrates the separate intersection mode of controlling diamond interchanges. This mode treats the two intersections as independent. A common cycle length and offset (ring lag) are used to coordinate the two intersections. Furthermore, this mode only permits lead-lead phasing.

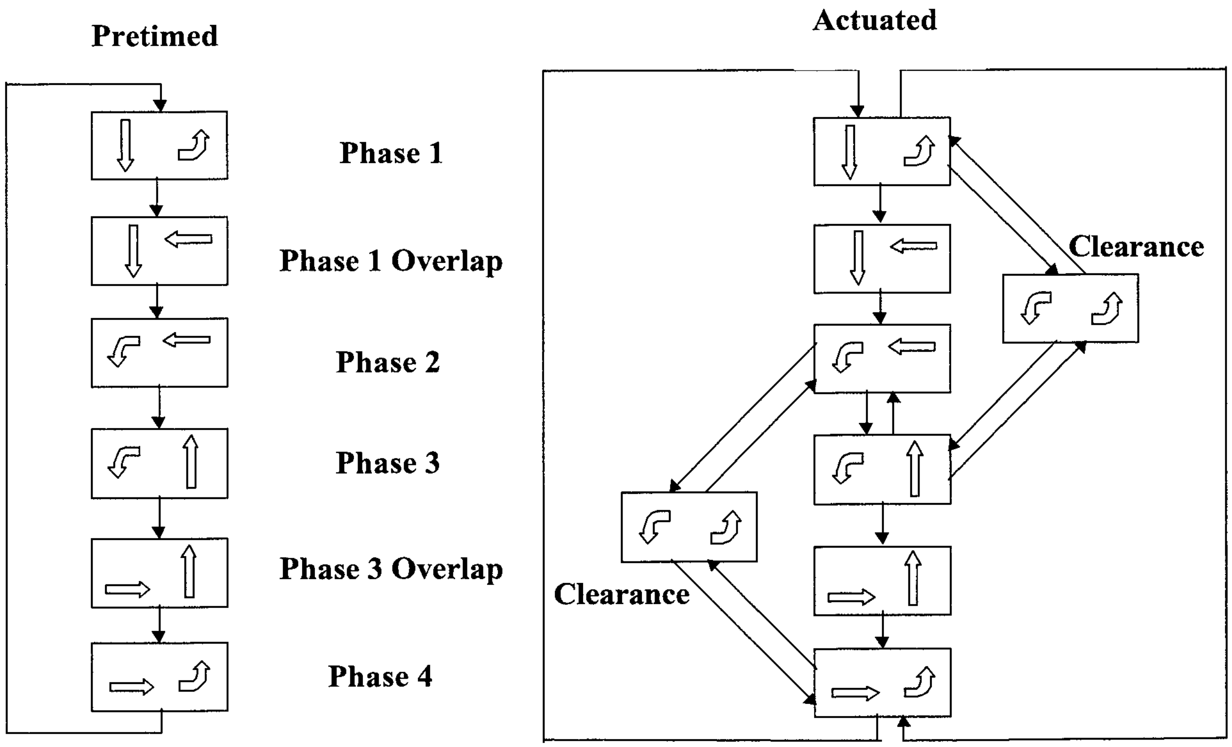


Figure 4. Texas Four-Phase Control Strategy.

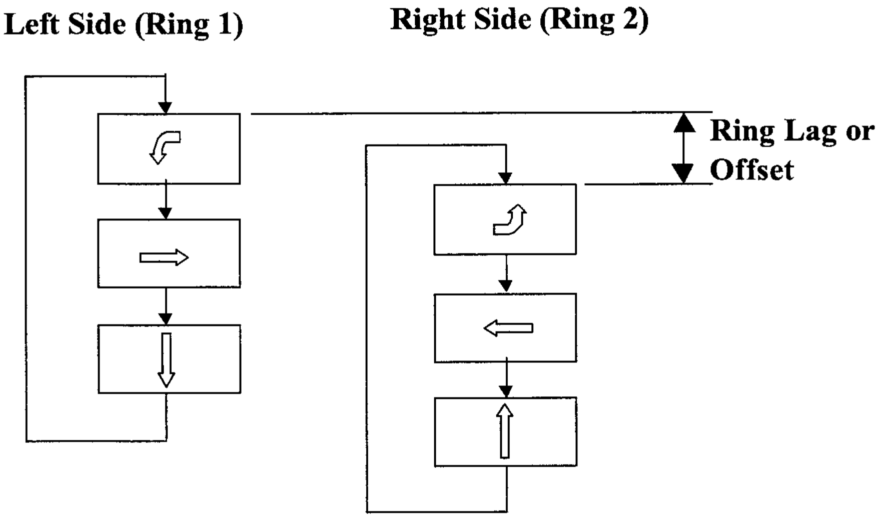


Figure 5. Separate Intersection Mode.

Other Operation Modes

As described above, the Texas diamond modes permit the use of only a subset of phase sequences possible at a diamond interchange. More flexible diamond interchange operation, however, can be achieved by using two separate controllers. Many modern controllers can be programmed to achieve the same results using features outside the preprogrammed diamond modes described above.

EXISTING TECHNOLOGY

Diamond interchanges have been the major focus of research for the past 30 years. Furthermore, there is an abundance of literature dealing with the description, design, and operation of these facilities (*1*). Table 1 provides a summary of the literature review on diamond interchanges. The first column of Table 1 provides a list of topics pertaining to diamond interchanges that have been addressed by previous research. Column 2 identifies the references corresponding to each item on the list. This list helps to identify and classify the existing state of technology and practice. The observations from this literature review are summarized below.

- Established tools (PASSER III and TEXAS) exist for analyzing and optimizing the operation of diamond interchanges. Guidelines also exist for the design and operation of diamond interchanges using existing tools.
- There is a lack of practical guidelines, procedures, and tools for applying a systems-level approach (that is, treating as one integrated system) to designing and operating signalized diamond interchanges and adjacent traffic signals.
- Although the need for inter-jurisdictional cooperation between multiple agencies is identified, no guidelines or policies are available for initiating and bringing about this cooperation to coordinate interchanges with adjacent traffic signals.

Existing Computer Models

A number of computer models are currently available to the traffic engineering community. This section provides a summary of their features and deficiencies.

PASSER III is specifically designed for diamond interchanges (*26*). PASSER III can analyze and optimize signal timings for minimizing delay within each interchange. The program explicitly considers all the 18 turning movements through a diamond interchange with one-way frontage roads and left-turning conflicts due to the close proximity of the two signals. PASSER III, however, does not have the capability to coordinate the diamond interchange with adjacent traffic signals. In addition, it can only analyze undersaturated conditions since its queue estimation logic treats queues as a vertical stack.

Table 1. Summary of Literature Review.

Areas of Diamond Interchanges	References
Characteristics, operational considerations, and measures-of-effectiveness	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25
Description, limitations, and applicability of models	14, 15, 16, 17, 25, 26, 27, 28, 29, 30
Comparison with other interchange forms	12, 19, 21, 22, 24, 31, 32
Frontage roads: operations, safety, progression	5, 7, 15, 11, 26, 34, 35
Design versus operation	2, 3, 6, 7, 36, 37, 38
Actuated control	9, 10, 13, 28, 39, 40
Capacity analysis	6, 12, 25, 41, 42
Description of PASSER III and user/application guides	7, 15, 18, 26, 43
Controllers, settings, and implementation	11, 18, 26, 39, 40
Retiming guidelines	16, 17, 18, 44
Field studies to evaluate strategies, and sign control	8, 9, 10, 13
Case studies to improve operations at specific locations	44, 45, 46
Detectors and detection issues	9, 10, 13
Real-time control and ITS	5, 30, 47
Benefit or benefit-cost analysis	23, 32
Survey-of-practice	25, 48
Recommendations for improvements in HCM methods	1, 25
Effects of trucks and of large/wide vehicles	49, 50
Coordination with adjacent signals – case studies	45, 51
TEXAS model	39, 40
Development of trend lines to forecast congestion	16, 17
Weaving on the arterial: analysis and models	25
Data requirements for operational analysis	18
Congested flow and related optimization models	52
Warrants for grade separation	23
Volume-based guidelines for stop-sign vs. signal control	53
Recommendations for improvements in MUTCD	8
Incident detection	54
Analysis of coordination with adjacent signals	55
Survey of state-of-art and state-of-practice	48

TEXAS model is a stochastic microscopic simulation package (*39*,*40*). It can simulate the operation of isolated signals and isolated diamond interchanges. It can be used to analyze the operation of a diamond interchange with various configurations of controllers and loop detectors. The main limitation of this model is its inability to simulate diamonds and adjacent traffic signals as one system.

PASSER II-90 (*56*) is a program for optimizing signal timings on signalized arterials. PASSER II does not consider the flow dependencies between two closely spaced signals and provides limited capabilities for coordinating diamond interchanges with adjacent signals. PASSER II is useful for interchanges with large interior distance where its two intersections can be treated independently. In addition, PASSER II is not applicable to saturated or oversaturated traffic conditions.

PASSER IV-96 (*57*) is a program for optimizing signal timings in arterials and multi-arterial networks. It has a limited capability to provide coordination of diamond interchanges with adjacent traffic signals and adjacent interchanges. For diamond interchange analysis and optimization, its deficiencies are similar to those of PASSER II. However, PASSER IV guarantees equal saturation splits for all critical movements and thus produces better results for near-saturated traffic conditions.

TRANSYT 7F (*58*) is a delay-based signal timing optimization/analysis program for signalized networks. It can be used for undersaturated as well as oversaturated traffic conditions. Like PASSER II and PASSER IV, it treats the two signals of a diamond interchange independent of each other.

Synchro (*59*) is a fairly recent tool for timing traffic signals. It is a delay-based program for optimizing signal timings. Its graphical user interface is better than all programs discussed here. The most recent version of Synchro (Version 4.0) has the ability to time diamond interchanges and can be used to coordinate diamond interchanges with adjacent signals on the arterial. However, the quality of its results is not known at this time.

CORSIM (*60*) is a microscopic-stochastic simulation model for roadway networks. It has two components: FRESIM and NETSIM. FRESIM can simulate freeways and ramps (with or without metering). NETSIM can simulate most configurations of intersections (stop sign control, yield control, and pretimed or actuated signal control) and arterials.

3. STATE OF PRACTICE SURVEY

INTRODUCTION

In the previous chapter, we provided a brief description of the state-of technology as it relates to the analysis and operation of diamond interchanges. This chapter summarizes the results of a survey conducted by the research team to ascertain the current practices of different transportation agencies in Texas for operating and evaluating signalized diamond interchanges. The survey was sent to either the traffic engineer or traffic operations director in each district of the Texas Department of Transportation and to the traffic engineering staff of the following cities, all located in Texas:

- Houston,
- Lewisville,
- Austin,
- Fort Worth,
- Lubbock,
- Amarillo, and
- Richardson.

The survey contained a total of 17 questions designed to solicit information about how different agencies operator and evaluate their diamond interchanges. Appendix A contains a copy of the survey.

Researchers sent the survey to all TxDOT districts and seven cities located in the state of Texas. Of those agencies that received the survey, 17 districts (65 percent of TxDOT districts) and four cities (57 percent of cities) replied to the survey. Three of the 17 districts that responded to the survey indicated that they did not have any signalized diamond interchanges under their control. Therefore, there were a total of 18 responses to the survey, a 55 percent response rate.

SURVEY RESULTS

This section describes the survey results. Here, the responses have been divided into several subsections.

Frequency of Evaluation

Question 1 asked the agencies how often they evaluated the operations of the diamond interchanges under their control. The purpose of this question was to determine if responding districts and cities have systematic programs for evaluating the operation of their diamond interchanges. A total of 17 agencies responded to the question. Fourteen (82 percent) agencies indicated that they evaluated the operations on their diamond interchanges "on an as needed basis" only. One district indicated that they evaluated their diamond interchanges "once a year," while two agencies (a TxDOT district and a city) indicated that they reviewed the operation of their diamond interchange "every 1-3 years."

Priorities and Objectives of Operation

Question 2 asked the agencies to rank, in priority order, several common objectives for operating diamond interchanges. The purpose of this question was to determine, in general, how agencies prioritize the operational problems that might commonly occur at a diamond interchange.

Table 2 shows means and modes of the responses received. The mean reflects the average ranking of all the responses to each objective, and the mode represents the most frequent ranking of all the responses.

Table 2. Ranking of Common Objectives for Operating Diamond Interchanges and Closely Spaced Intersections.

Operational Objective	Mean	Mode
Prevent queues on the frontage road from interfering with existing ramp traffic	1.3	1
Maintain good progression on the arterial street	3.8	4
Prevent queues internal in the interchanges from blocking upstream intersections	3.6	3
Balance delays on external approaches to the interchange	3.8	2
Provide access to properties adjacent to the interchange	6.6	7
Prevent queues from adjacent signalized intersection from blocking interchange intersections	4.1	5
Prevent queues from interchange intersections from blocking adjacent signalized intersection	4.5	6

As can be seen from Table 2, preventing queues on the frontage road from interfering with traffic exiting from the upstream ramp seems to be the top priority of all the agencies responding to the survey (including the cities). Beyond this objective, agencies were divided as to their next highest priorities for operating diamond interchanges. Respondents ranked the following four objectives similarly:

- preventing internal queues within the interchanges from blocking upstream intersections,
- maintaining good progression on the arterial street,
- balancing delays on external approaches to the interchange, and
- preventing queues from adjacent signalized intersection from blocking interchange intersections.

In general, most agencies consistently ranked these four objectives in the same order (i.e., the mean of the rankings and the mode of the ranking were similar). The one exception to this observation is balancing delays on the external approaches to the interchange. Six agencies felt that balancing delays on the external approaches to the interchange was a high priority (ranking it as their second highest priority), while five agencies felt that balancing delays on the external approaches was a low priority (ranking it either five or six in order of priority).

The objective that ranked lowest by all the respondents was providing access to properties adjacent to the interchange. Only two districts, both of which would be considered rural districts, did not give this operating objective the lowest ranking. For the most part, the cities ranked the objectives in a similar order as the districts. This suggests that, in general, cities have similar objectives to those of the TxDOT districts in operating the diamond interchanges in their jurisdiction.

Techniques Utilized for Evaluation

Question 3 asked recipients to identify the techniques that they commonly use to evaluate the operations of the diamond interchanges under their jurisdiction. Table 3 summarizes the results to this question.

As seen in Table 3, all agencies responding to the survey indicated that, at a minimum, they use field observations to assess the operations of their diamond interchanges. Over three-quarters of the respondents indicated that they perform manual turning movement counts as part of their evaluation process. Over two-thirds of the respondents indicated that they commonly use a computer optimization program to help them assess the effectiveness of the diamond interchanges in their jurisdictions. Slightly more than one-third of the respondents indicated that they commonly use a computer simulation program to assess operations.

Table 3. Commonly Used Techniques to Evaluate the Operation of Diamond Interchanges.

Evaluation Technique	Percent of Agencies Using Technique
Field Observations	100%
Manual Turning Movement Counts	78%
Automatic Traffic Volume Counts	40%
Computer Optimization	71%
Computer Simulation	39%
Other	11%

The findings from this question suggest that simulation should not be considered as a commonly used technique in analyzing the operations of diamond interchanges, and that any procedure that uses simulation as the basis of the analysis would not be used by more than one out of three agencies.

Use of Computer Tools

In the fourth question of the survey, we asked the recipients to identify what simulation/optimization tools they used to analyze the operations of diamond interchanges. Table 4 summarizes the responses.

Table 4. Percent of Agencies Using Different Tools to Evaluate the Operations of Their Diamond Interchanges.

Simulation/Optimization Tool	Percent of Agencies Using
Highway Capacity Manual/ Highway Capacity Software	21%
PASSER II	33%
PASSER III	69%
PASSER IV	21%
SYNCHRO	31%
NETSIM/CORSIM	6%
TRANSYT	13%
Other	21%

Table 4 indicates that the majority of agencies will use a software package such as PASSER III to evaluate their diamond interchanges. Three possible explanations why PASSER III is used most commonly include the following:

- PASSER III is readily available to TxDOT and other local agencies,
- most TxDOT districts know that PASSER III was designed specifically to develop optimal signal timings for diamond interchanges, and
- PASSER III is relatively easy to code, compared to other simulation/evaluation models.

It is interesting to note that very few agencies use NETSIM/CORSIM or TRANSYT to evaluate the performance of diamond interchanges. Researchers believe that agencies are reluctant to use these models to evaluate diamond interchanges because of their complexity and extensive data requirements.

Criteria for Selecting Type of Operation

Researchers designed questions 5 through 7 to ascertain the criteria used by different agencies to determine the type of operations used at diamond interchanges. Recipients were asked under what volume and traffic conditions would they operate the intersections using one of the following strategies:

- two independent intersections,
- a three-phase timing plan, and
- a four-phase timing plan.

Tables 5 through 7 show how the different agencies and districts responded to these survey questions.

Table 5. Criteria for Operating a Diamond Interchange as Two Separate Intersections.

District/Agency	Criteria for Operating Interchange as Two Separate Intersections
Fort Worth	Where frontage roads are over 600 ft. apart.
City of Fort Worth	Under conditions where the signal was marginally warranted, with very light traffic on all external approaches.
Bryan	Not sure volume of traffic is an issue. The distance between signal is the main concern. Any distance greater than 600-800 ft. should be looked at as two separate intersections.
Paris	Extremely wide intersections, very little left-turn traffic and very light traffic. Long distance between frontage roads. Lots of left-turn storage.
Lubbock	Light volume frontage road intersections. Actuated operation with green rest on the arterial should be used.
Amarillo	Primarily when the internal distance between intersections is greater than 600 ft. Light traffic volumes.
Austin	Never.
Corpus Christi	Low traffic volume and large separation (over 400 ft.).
City of Amarillo	Traffic volume would be low. Geometric conditions— the distance between the frontage roads would be greater than normal (700 ft. or greater); usually caused by street crossing frontage roads at a skew.
Waco	Do not currently do this in district. To use this type of operation, there needs to be a great distance between the frontage roads, and there needs to be light traffic volumes (but if the volumes are light, it probably would not warrant a signal).
City of Lewisville	Low volume, low interior turning movements. Frontage roads spacing conducive to three-phase operation (500 ft. or more). Late night operation at a three-phase diamond.
Atlanta	Light traffic volumes.
San Antonio	The intersections would have to be more than the normal distance apart — then operate with coordinated operation — though not as efficient.
Beaumont	Low volume, rural, separation that allows for adequate left-turn storage, interconnected for basic progression.
Houston	Widely spaced frontage roads, especially when the adjacent signals are close to the diamond interchange, and very light turning movements and traffic.
City of Houston	Light turning volumes (internal); intersection interconnected (physically) to maintain coordination; adequate spacing with respect to volumes.

Table 6. Criteria for Operating Diamond Interchange with Three-Phase Operation.

District/Agency	**Criteria for Operating Interchange as with Three-Phase Operation.**
Fort Worth	Use TTI guidelines – volume and distance. For the distance criteria, the frontage road spacing is between 200 ft. and 500 ft.
City of Fort Worth	When the frontage road volumes are heavy with mostly straight through movements, and the arterial volumes are light. When the arterial volumes are heavy, usually peaking from one direction or the other, and frontage road volumes are light. When all traffic volumes are moderate.
Bryan	On modestly spaced interchanges – between 400 and 600 ft. – with any level of traffic.
Paris	Balanced left-turn movements with adequate left-turn storage. Frontage road traffic lighter than arterial.
Amarillo	1) Separate internal left-turn bays; 2) heavy through traffic; and 3) light ramp traffic (frontage road traffic).
Austin	Only if left-turn volume is slight and arterial heavy.
Corpus Christi	Large separation between frontage roads for storage and most traffic on frontage roads.
City of Amarillo	*Traffic volumes*: a) low left-turn traffic volume between frontage roads; b) low semi-truck traffic; c) crossing arterial volumes primary one direction; d) low frontage road traffic volumes. *Geometric conditions*: ample left-turn storage space between frontage roads (minimum 300 ft.).
Waco	Generally use three-phase operations where there is a great distance between frontage roads.
City of Lewisville	Frontage road spacing > 300-400 ft. where there isn't an "overloaded" interior left-turn movement.
Atlanta	Light traffic volumes.
San Antonio	Only when needed to bypass main-lane traffic to frontage road (as in a main-lane closure).
Beaumont	Low frontage road volumes or low left-turn volumes with adequate left-turn storage bays.
Houston	1) light traffic with light left-turns; 2) if the through volumes are very heavy and no U-turns or left-turns.
City of Houston	Light frontage road turning volumes (i.e., adequate storage space); heavy through volumes on arterial and/or frontage roads; light left-turn volumes on arterial.

In general, the consensus of the survey respondents were as follows:

- The diamond should be operated as two separate intersections when there is a large separation (more than 600 ft.) between the frontage roads. This mode of operation works well when intersection volumes are light with limited turning movements (such as at rural interchanges).
- Three-phase operation should generally be used when there are heavy movements on either the frontage roads, or the arterial, or both. Three-phase operation also tends to work well when there are balanced left-turn movements with adequate internal

storage. Three phase operations should be used when the intersections are spaced between 400 and 600 ft. apart.

- Four-phase operation is generally used when the spacing between intersections is tight (i.e., 250 ft.), when traffic volumes are relatively high on at least three approaches, and when there is a need to prevent left turns from spilling back into the through lanes.

Table 7. Criteria for Operating Diamond Interchange with Four-Phase Operation.

District/Agency	Criteria for Operating Interchange as with Four-Phase Operation.
Fort Worth	Less than 250 ft. spacing between frontage roads.
City of Fort Worth	When the traffic volumes are mostly making interchange movements, such as movements from the ramps to the arterial and from the arterial to the ramps.
Bryan	Closely spaced intersections.
Paris	Heavier volumes, all approach volumes fairly even.
Amarillo	High traffic volumes on at least three approaches.
Austin	When all directional movements are heavy.
Corpus Christi	Even flow of traffic all the way around.
City of Amarillo	*Traffic Volumes*: heavy left-turn volumes, moderate to heavy volumes in some or all approaches. *Geometric Conditions:* frontage roads less than 300 ft. apart.
Waco	This is the primary mode of operating diamond signals in the district. Recommend operating most signals in district in this mode.
City of Lewisville	Closely spaced frontage roads < 200 ft. or where the interior left-turn volume is so high that you have spillback through the upstream frontage road signal.
Atlanta	High traffic volumes and turning movements.
San Antonio	This district uses four-phase operation at all diamond interchanges with the exception of where there are no overpass bridges.
Beaumont	High volumes; limited left-turn storage.
Houston	Most all locations – particularly with moderate to heavy left-turn movements. Closely spaced interchanges where gridlock could occur.
City of Houston	Tight spacing; heavy frontage road turning volumes; heavy left-turn volumes on arterial.

Most Common Operational Strategy

Researchers asked the respondents to indicate the number of interchanges they operated in each of the different operating modes. Table 8 summarizes the responses received. As can be seen from Table 8, most of the respondents indicated that they operated a majority of their diamonds in a four-phase mode. Larger cities such as Houston, Fort Worth, Austin, and Corpus Christi (where traffic congestion and oversaturation tend to be a bigger problem) generally operate their signals in a four-phase mode. Only a few agencies indicated that they switch between three-phase and four-phase operation based on the time of day.

Table 8. Number of Interchanges in Different Cities/District by Operating Mode.

City/District	Four-Phase Operations	Three-Phase Operations	Two Separate Intersections	Alternate Between Three-Phase and Four-Phase by Time-of-Day
Fort Worth	34	1	12	0
City of Fort Worth	23	19	11	1
Bryan	0	2	7	0
Paris	3	0	0	0
Lubbock	0	0	1	0
Austin	45	3	0	0
Corpus Christi	41	0	0	0
Lufkin	6	0	0	0
City of Amarillo	13	2	1	0
Waco	8	1	3	0
City of Lewisville	0	3	4	1
Atlanta	0	0	6	0
San Angelo	0	10	0	0
San Antonio	133	5	0	0
Beaumont	0	1	0	0
Houston	125	30	15	0
City of Houston	100	15	25	3
Total	**531**	**92**	**85**	**5**

Other Strategies

Question 9 asked survey respondents to list any successes that they might have had using strategies other than those listed above. Table 9 summarizes the various responses to this question. Most of the innovative strategies involve the use of multiple controllers to operate the diamond. By using multiple controllers, engineers have more flexibility in the timing plans that they can implement in response to specific problems.

Table 9. List of Innovative Strategies Used by Districts for Operating Diamond Interchanges.

District/City	Response
Paris	Three intersections are running eight-phase NEMA standard. Each side of the interchange is running off of one ring, making it independent of the other.
Austin	Use standard dual quad ring structure at diamond interchanges. By completely overlapping all approaches, we have enabled the ease of sequence change by deleted, adding, or manipulating phases. The only drawback is that these locations become extremely complex.
City of Lewisville	Use separate controllers on each frontage road. This allows us a few more options over agencies that run a diamond off a single controller. One example is the IH35E interchange with FM 3040, where the interior protected left-turn phase is called twice per cycle. This was installed to help a problem where the downstream jughandle fed by this signal was overloaded with a single protected service once per cycle.
Atlanta	Don't use diamond controllers at three interchanges. Use a single controller with six phases and four overlaps. Traffic volumes are relatively light. At the other three interchanges, use two separate controllers, one for each side of the interstate. We have two-way frontage roads on both sides of the interchange. The ramp does not enter into the feeder roads. Coordination is provided on both sides. Two of these interchanges are pretimed.
Beaumont	Phase plus overlaps.
Houston	With directional left-turn movements on arterial under some conditions, you can modify the three-phase sequence.
City of Houston	We try leading left-turns at one service road and lagging at the other. We found three-phase diamond with both lagging left-turns works out better.

Actuated versus Pretimed Control

The survey asked each district or agency whether most of the diamond interchanges in their jurisdictions operated in either an actuated or pretimed mode. Over 76 percent of the respondents indicated that the signals at the diamond interchanges in their jurisdictions were primarily actuated or semi-actuated, while the remaining 24 percent of the survey respondents indicated that they operated their signal in a pretimed mode. With the exception of the City of Houston, most of those agencies that indicated they operated their signal in a pretimed mode were from rural TxDOT districts (Bryan, Lubbock, and San Angelo).

Solutions to Specific Operational Problems

Researchers asked a series of questions to solicit ideas on how to address specific operational problems that might occur at a diamond interchange. Tables 10 through 14 summarize the responses received for each question.

Table 10. Strategies Employed by Agencies to Correct Queues from Spilling Back from One Ramp Intersection through the Other Intersection.

District/City	Response
City of Fort Worth	For us, this is only a problem in the three-phase mode. To correct, we then use a four-phase timing plan.
Bryan	Conduct turning movement counts. Use PASSER III or SYNCRHO to retime signals. Maybe use a different phasing scheme for the left turns.
Austin	Conduct delay runs. Conduct analysis using computer simulations. Adjust the offsets and splits.
Corpus Christi	Use shorter cycle lengths.
City of Lewisville	Adjust signal timing.
Atlanta	Timing plan changes.
Houston	Change to four-phase operation or shorten cycle length. Retime the signals, modify the lane assignments, and install additional travel lanes.
City of Houston	Adjust timing. Install changeable lane assignment signs. Relocate ramps.

Table 11. Strategies Employed by Agencies to Correct Queues from a Left-Turn Lane from Extending into the Through Lanes.

District/City	Response
Fort Worth	Add left-turn capacity by using any of the following techniques: 1) add a lane or share a left-turn/through lane, 2) use protected/permissive section head, 3) use a fiber optic lane assignment sign with variable message for shared lane.
City of Fort Worth	For us, this is only a problem in the three-phase scheme, and we would then use a four-phase scheme.
Bryan	Conduct turning movement counts. Use PASSER III or SYNCRHO to retime signals. Maybe use a different phasing scheme for the left turns.
Austin	Conduct traffic counts. Extend lanes. Adjust split times. Optimize peak plans.
Corpus Christi	Provide continuous left-turn bays and dual left turns to the frontage roads.
City of Lewisville	Call left-turn phase twice per cycle.
Atlanta	Timing plan changes.
San Antonio	Dedicate left-turn lane and implement permissive left-turn/straight through lane if enough lanes are available.
Houston	Change to four-phase operation or use a modified three-phase if the problem is directional. Shorten cycle lengths in some cases. Install lane assignment signs, or install additional lanes.
City of Houston	Evaluate/deploy shared lane to increase turning capacity. Evaluate/modify signal timing.

Table 12. Strategies Employed by Agencies to Correct Queues from the Frontage Road Signal Blocking the Off-Ramp.

District/City	Response
Fort Worth	Move the off ramp to a desirable distance, if possible.
City of Fort Worth	Invoke maximum times to control the intersection cycle length, and even penalize the other three external movements to help the heavy ramp phase.
Bryan	Give more time to the frontage road phase. Conduct traffic counts and investigate retiming signal.
Paris	Reduce the maximum times to cause the phases to cycle more often.
Austin	Conduct traffic counts. Conduct delay runs. Make adjustment to the splits. Optimize peak plans.
Corpus Christi	Use shorter cycle length and evenly distribute the timing on all approaches.
City of Amarillo	Adjust signal timing to force queues to arterial approaches.
Waco	Increase the signal timing on the frontage road. Make sure that times are not too long on the other approaches.
City of Lewisville	Adjust signal timing.
Atlanta	Change timing plan.
San Antonio	Increase the maximum green time on the ramp/frontage road approaches if possible. Fine tune or shorten the other approaches if possible. Relocate exit ramp back from interchange. Install additional storage lanes.
Beaumont	Use queue detectors to activate MAX II values to reduce arterial times while increasing frontage road times to clear off ramps.
Houston	Retime traffic signal. Install/modify lane assignments. Change phasing. In extreme cases, relocate ramp or add lanes.
City of Houston	Evaluate/modify signal timing. Install changeable lane assignment signs.

Table 13. Strategies Employed to Correct Queues from a Frontage Road Signal from Backing into an Adjacent Signalized Intersection on the Arterial.

District/City	Response
Fort Worth	Develop efficient coordination plan.
City of Fort Worth	At I-20 and Hulen this occurs. The cross street filters the arterial without causing major cross street delay.
Bryan	Adjust timings at adjacent signal to not allow unserviced flow to queue (i.e., reduce green time on adjacent signal).
Austin	Conduct traffic counts. Extend lanes. Adjust split times. Optimize peak plans.
Corpus Christi	Provide progression with city signals at peak times.
City of Amarillo	Force progression. Adjust timing to leave space between signals clear for side street traffic to enter.
City of Lewisville	Use MAX call on a leading turn at the adjacent signal to "gate" (or meter) the vehicles approaching the diamond.
Atlanta	Timing plan changes.
Houston	Optimize timing and phase.
City of Houston	Coordinate operation so that queue between signals is flushed out. Change phase sequence at adjacent signalized intersection, when appropriate.

Table 14. Strategies Employed to Correct Queue Backup from an Adjacent Signalized Intersection on the Arterial into the Frontage Road Signal.

District/City	Response
Fort Worth	Develop efficient coordination plan.
Bryan	Adjust timings at adjacent signal (i.e., give more green time).
Austin	Adjust offsets.
Corpus Christi	Provide progression with city signals at peak times.
City of Lewisville	"Gate" (or metering) will help the problem when the minor street is actuated and can return slack time to the left turn.
Atlanta	Timing plan changes.
San Antonio	Does not occur in four-phase operation. User shorter maximum green times for this if using three-phase operation.
Houston	Retime traffic signal. Use double cycle at one or other in the worst case. Tax the cross street traffic at the arterial, or diamond may gridlock and back to main lanes.
City of Houston	Evaluate/modify timing at adjacent signal and diamond. Normally, the diamond is the critical choke point.

Use of Special Controller Features

The survey asked respondents about what special controller features (for example, conditional servicing, detector switching, phase reversals, protected/permissive left-turn phasing, etc.) they use to address specific operational problems at diamond interchanges. Ten agencies responded that they have used special controller features. In most cases, protective/permissive turn phases and detector switching appear to be the most commonly used special controller features. Table 15 summarizes the responses of the survey recipients.

Types of Adjacent Signals and Their Impact on the Diamond

The practitioners were asked about what type of intersection (a three-way "T" intersection or a four-way, quad left intersection) has a greater impact on the operations of the interchange when it is in close proximity to the diamond interchange. None of the survey respondents believed having a three-way "T" intersection adjacent to the diamond caused greater operational problems than a four-way intersection. On the contrary, 71 percent of the survey respondents indicated that having a four-way intersection adjacent to the diamond would likely cause more operational problems. Twenty-four percent of the respondents indicated that the operational problems were about the same for each intersection type.

Table 15. Summary of Special Controller Features Used to Address Operational Problems at Diamond Interchanges.

District/City	Response
City of Fort Worth	Use controller software that allows switching from three-phase to four-phase by time-of-day or by use of queue detectors. In the past, we had several diamonds that were capable of switching from three-phase to four-phase upon detection of congestion within the internal area; however, we experienced that the three-phase scheme worked well full time at some diamonds and at others, although higher intersection delay was experienced, four-phase was satisfactory.
Bryan	Conditional service is used on SH30/SH6 to allow additional servicing of the interior left turns (light frontage and arterial approaches on that site). Phase reversals to change from leading to lagging if delay is reduced. Protected/permissive on all left turns that are not dual lefts.
Paris	Detector switching.
Austin	Use volume density control. It allows the maximum times to increase incrementally, based on vehicle-actuated volumes. Phase reversal can be used to vary the sequence to optimize traffic flow.
Corpus Christi	Protected/permissive left-turn phasing.
City of Lewisville	Because the problem occurs at saturation, conditional service or reservice will not help much. The controller either has to provide the ability to run a phase twice per cycle and use an overlap to accomplish this. Lead-lag is a must and the yellow-trap must be addressed if protected/permissive operation is used (use the Dallas display or make the lead turn protected only).
Atlanta	Protective/permissive left-turn phasing using Dallas display.
San Antonio	Detector switching is used on frontage roads, and detector drop is used on arterials to sharpen operation and eliminate stragglers from over-extending phases (proper loop spacing and gap time must be used).
Houston	Use protective/permissive left-turn phasing where possible. Detector switching for less dead time on frontage road.
City of Houston	Occasionally use the phase reversal to make it a three-phase diamond with lagging left-turns.

Access Management Strategies

Researchers also asked about the kind of access restrictions and controls respondents have implemented to correct operational deficiencies at or near diamond interchanges. The majority (53 percent) of the survey respondents indicated that they have not tried any access restrictions near problem diamond interchanges. Twenty-four percent of the survey respondents indicated that they have tried either prohibiting left turns into driveways and access points. Twenty-four percent of the respondents have also rechannelized driveways to correct operational deficiencies near diamond interchanges. Eighteen percent of the respondents indicated that they have installed traffic signals to address access problems. Other reported improvements include the following:

- minimize access points with desirable spacing,
- reverse order of ramps,
- increase lanes on frontage roads, and
- upgrade intersection to widen approaches and increase storage capacity.

Ranges of Cycle Length Used

The survey asked each agency to indicate the average and highest cycle lengths they used to operate all of the diamond interchanges in their jurisdictions during the AM-Peak, Off-Peak, and PM-Peak periods. Table 16 provides a summary of responses to this question.

Table 16. Average and Range of Cycle Lengths Reportedly Used by Agencies in Operating Diamond Interchanges.

Peak Period	Average of Cycle Lengths	Range of Cycle Lengths
AM-Peak: Average	98 sec	80 – 160 sec
Highest	138 sec	70 – 280 sec
Off-Peak: Average	86 sec	60 – 160 sec
Highest	118 sec	70 – 280 sec
PM-Peak: Average	89 sec	80 – 160 sec
	113 sec	70 – 280 sec

Special-Event Timing Plans

Each survey recipient was asked to indicate if they used any special timing plans to accommodate special event traffic (such as holidays, sporting events, etc.) at any of their diamond interchanges. Sixty-five percent of the survey respondents indicated that they did not use any special timing plans to accommodate special event traffic, while thirty-five percent indicated that they did use special timing plans.

The survey asked respondents to indicate the circumstances in which the special timing plans were used. Four of the respondents indicated that they use special timing plans near shopping malls with adjacent diamond interchanges in November/December. One respondent indicated that they have a special preempt flash that can be activated by a switch in the police panel in the event of a hurricane.

Existing Sites with Operational Problems

Question 17 asked survey recipients to list and describe three problem locations in their jurisdictions. Table 17 summarizes their responses.

Table 17. Potential Problem Locations Identified in Survey.

District/City	Problem Locations
Fort Worth	FM 1709 / SH 114 and Park St. in Grapevine US 287 / Walnut Creek Dr. and Country Club Dr. IH 820 / SH 26 and FM 1935 in North Richland Hills
City of Fort Worth	IH 20 with Hulen St. – Full diamond intersection with frontage road U-turn lanes. Hulen runs North/South. This intersection has a signalized driveway at Westdale about 500 ft. to the north of I 20, with queues frequently backing to and through Westdale intersection.
Bryan	FM 60 / SH6 and Glenhaven – had to retime Glenhaven (city signal) to not allow overload of diamond SH 6/ SH 30 and Post Oak Mall SH 6 / FM 1179 and Freedom Drive
Austin	FM 620 / FM 734 (Parmer Lane) IH 35 / FM 1325 – Oversaturation on all approaches in the AM-Peak. Oversaturation on the southbound, westbound, and northbound frontage roads during the Noon-Peak due to previous signal locations. LP 1 / FM 734 and HEB driveway – The proximity of the HEB signal to LP 1 diamond is less than 200 feet.
Paris	US 82 / SH 91 – small left-turn storage (five vehicles) with limited ramp storage – this forces us to run four-phase to keep left-turns clear and limit our cycle lengths to keep ramps clear. The arterial (SH 91) is saturated and backs up to another signal.
Corpus Christi	SH 358 / Everhart – arterial signal close and Everhart at capacity during peak hours. SH 358 / Staples – same as above. SH 358 / Airline – same as above.
Lufkin	US 59S – Intersections are very close with a lot of side street traffic. US 190 in Livingston.
City of Amarillo	Have diamond interchange in close proximity to the primary regional shopping mall for the area on one side and the primary hospital and medical center on the other side. The shopping mall creates the biggest problem during the Christmas season. The medical center continues to grow from the other side. The mall side is also on the route to a Wal Mart 2 miles downstream.
City of Lewisville	IH 35E / SH 121 – six lane expressway with 60,000 vpd and 30% trucks crossing IH 35E. Very unusual geometrics. Frontage roads 600 ft. apart with two four-way signals 600-700 ft. from the diamond. Switches from three-phase to four-phase by time-of-day. IH 35E / FM 1171 (Main Street) – signal at Edmonds (T intersection) within 200 ft. of signal. IH 35E / FM 3040 – jughandles back through the interior left movements because vehicles cannot enter the frontage road easily.
Atlanta	IH 30 / Richmond Rd. – ramps and frontage roads are separate and within 100 ft. of each other. Basically, there are four intersections at this interchange. IH 30 / Summerhill Rd. – Geometry is same as above.
Houston	IH 45 / LP 336N – Overcapacity diamond in middle of an overcapacity arterial intersection closely spaced to diamond. IH 45 / FM 518 – Overcapacity diamond at end of arterial. One intersection 350 ft. away IH 10 / Fry Rd. -- Overcapacity widely spaced diamond in middle of another agency's arterial.
City of Houston	Sam Houston Parkway / Westheimer – Overcapacity. Difficult to provide two-way progression on arterial. SH 6 / IH 10 Beechnut / Sam Houston Parkway

4. CAPACITY ANALYSIS AND TIMING OF DIAMOND INTERCHANGES

INTRODUCTION

In Chapters 2 and 3, we presented an overview of current technology and the results of a state-of-practice survey. The review of literature showed that there is a lack of operational guidelines and tools for diamond interchanges facing congested conditions, especially those located close to adjacent traffic signals on the arterial. The survey identified key operational issues and priorities. The survey also identified the need for easy-to-use procedures for the analysis and optimization of diamond interchanges and adjacent traffic signals.

In this chapter, we describe a simple technique for analyzing diamond interchanges and provide guidelines for coordinating diamond interchanges with adjacent signals on the arterial. The procedures described in this chapter utilize the standard procedures for calculating phase times. We conclude the chapter with a set of guidelines for analyzing and timing diamond interchanges.

ANALYSIS OF CONTROL STRATEGIES

In this section, we first present some notation and definitions. Then, we describe a procedure to analyze the capacity of the three control strategies for diamond interchanges described in previous chapters. Finally, we describe a simple procedure for coordinating an interchange with an adjacent traffic signal.

Notation

Figure 6 illustrates the standard NEMA phase numbering scheme for a diamond interchange. We use the following definitions in the following subsections:

C : cycle length, seconds
ϕ_i: phase time for movement i, seconds
y_i: volume to saturation flow ratio for movement i
Φ_{LR}: overlap from left to right (offset), seconds
Φ_{RL}: overlap from right to left, seconds
Φ: total overlap, seconds
l: lost time per phase, seconds
x: distance needed for a stopped vehicle to achieve the design speed, feet
a: acceleration rate, feet/sec^2
s: design speed, mph
V_{max}: design speed, feet/sec
d: link distance (stop-bar to stop-bar), feet

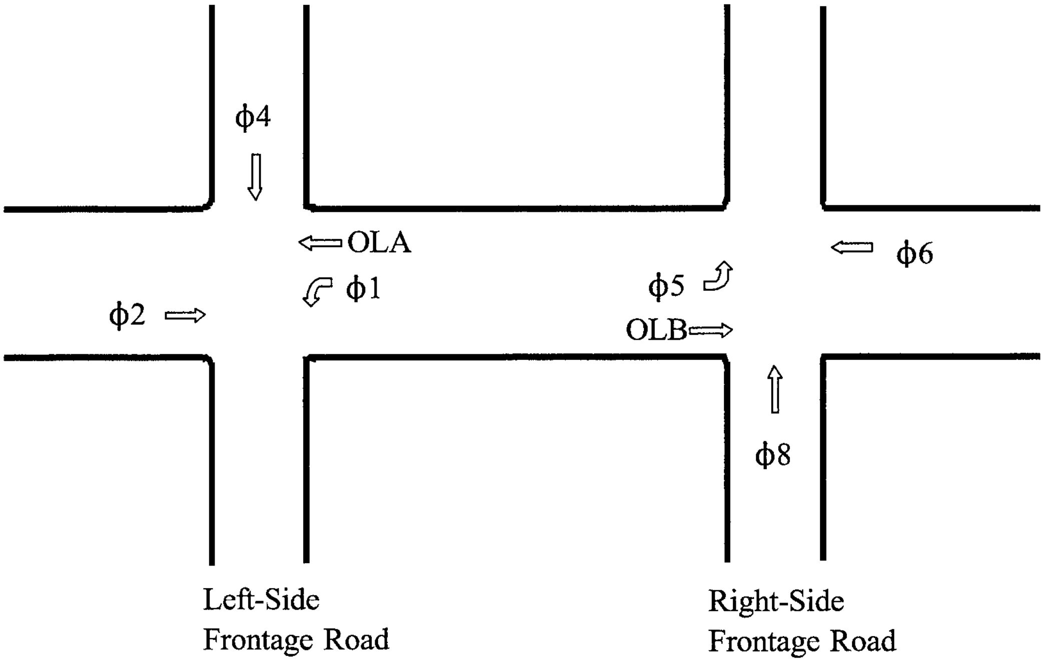


Figure 6. NEMA Phase Numbering Scheme for a Diamond Interchange.

Diamond Interchange Phasing

A diamond interchange is a simple case of two closely spaced traffic signals with one-way cross streets (frontage roads or ramp terminals). However, origin-destination distributions of traffic flowing through a diamond interchange are significantly different from that for two signals on an arterial, requiring special treatment. As mentioned in an earlier chapter, engineers commonly used Texas three-phase and TTI four-phase operations at signalized diamond interchanges in Texas. In the following sections, we present a detailed description of these strategies.

As mentioned in Chapter 2, coordination of the two intersections of a diamond interchange requires that they be operated using a common cycle length. Thus, the following equations always hold:

$$\phi_1 + \phi_2 + \phi_4 = C$$
$$\phi_5 + \phi_6 + \phi_8 = C$$

Texas Three-Phase Strategy

Texas three-phase strategy uses lag-lag phasing sequence. This strategy first serves both frontage roads (ramps) followed by main-street through traffic and then the interior left-turn movements. The calculation of the green splits for Texas three-phase is similar to that of Webster's formula. The difference is that the green splits for the frontage roads must be the same for both the left and right intersections. The detailed calculation is as follows:

$$\phi_4 = \phi_8 = \frac{\max(y_4, y_8)}{\max(y_1 + y_2, y_5 + y_6) + \max(y_4, y_8)} \times (C - 3l) + l$$

$$\phi_i = \frac{y_i}{y_1 + y_2} \times (C - \phi_4 - 2l) + l \qquad i = 1,2$$

$$\phi_i = \frac{y_i}{y_5 + y_6} \times (C - \phi_8 - 2l) + l \qquad i = 5, 6$$

As can be seen, the above calculations do not take into consideration the distance between the two intersections. Thus, Texas three-phase provides the same timing plan for a particular demand pattern no matter how wide the interchange is. However, in reality, the distance between the two signals does play an important role because of flow dependency between the two signals. We use a hypothetical balanced-demand case and four distance (100, 300, 500, and 700 feet) scenarios to illustrate how distance affects through progression for the Texas three-phase strategy. Figure 7 illustrates these situations for a cycle length of 60 seconds. In this example, we use appropriate travel times for the assumed distances. In the next section, we will present a description of the procedure for calculating travel times for use in the analysis and timing of diamond interchanges.

As can be seen from Figure 7, good through-progression for arterial traffic exists for a distance of 100 feet between the two intersections. One can also see that the arterial traffic wishing to turn left at interior approaches must wait for 9 seconds before the left-turn phases start. Increasing the distance to 300 feet still maintains full through-progression for arterial traffic; however, the waiting time for arterial traffic wishing to turn left at the downstream signal reduces. Increasing the distance to 500 feet results in perfect progression for arterial through and left-turn traffic. Perfect through- and left-progression for arterial traffic continues to exist as the distance increase to 700 feet. However, distances longer than 700 feet will result in interior delay to some arterial traffic entering the interchange that is at times close to the termination of exterior through phase. This wait will depend on the length of frontage road phase (in this example, a maximum of 22 seconds for the first vehicle to stop). In summary, this strategy provides good through progression for arterial traffic. Interior left-turn vehicles from the arterial approaches however, may have to stop and experience delay. The amount of this delay depends on the travel time and length of through phase at the downstream intersection.

As for the frontage road (ramp) left-turn vehicles, one can see from Figure 7 that vehicles going through at the downstream intersection may experience delay. The amount of this delay depends on the length of the frontage road phase and the travel time. In fact, delay to these vehicles will occur whenever frontage road phase is larger then the travel time. As long as there is sufficient storage space (a function of interior distance and number of lanes) for these vehicles, the interchange will operate well. Furthermore, the U-turn vehicles (vehicles wishing to turn left at the downstream signal) will experience the longest delay. As shown in the figure, all of these vehicles will stop when the interior distance is less than or equal to 500 feet. There should be sufficient storage space to ensure that these vehicles do not spillback from the left-turn bay or into the upstream traffic signal. The best alternative is to provide U-turn lanes.

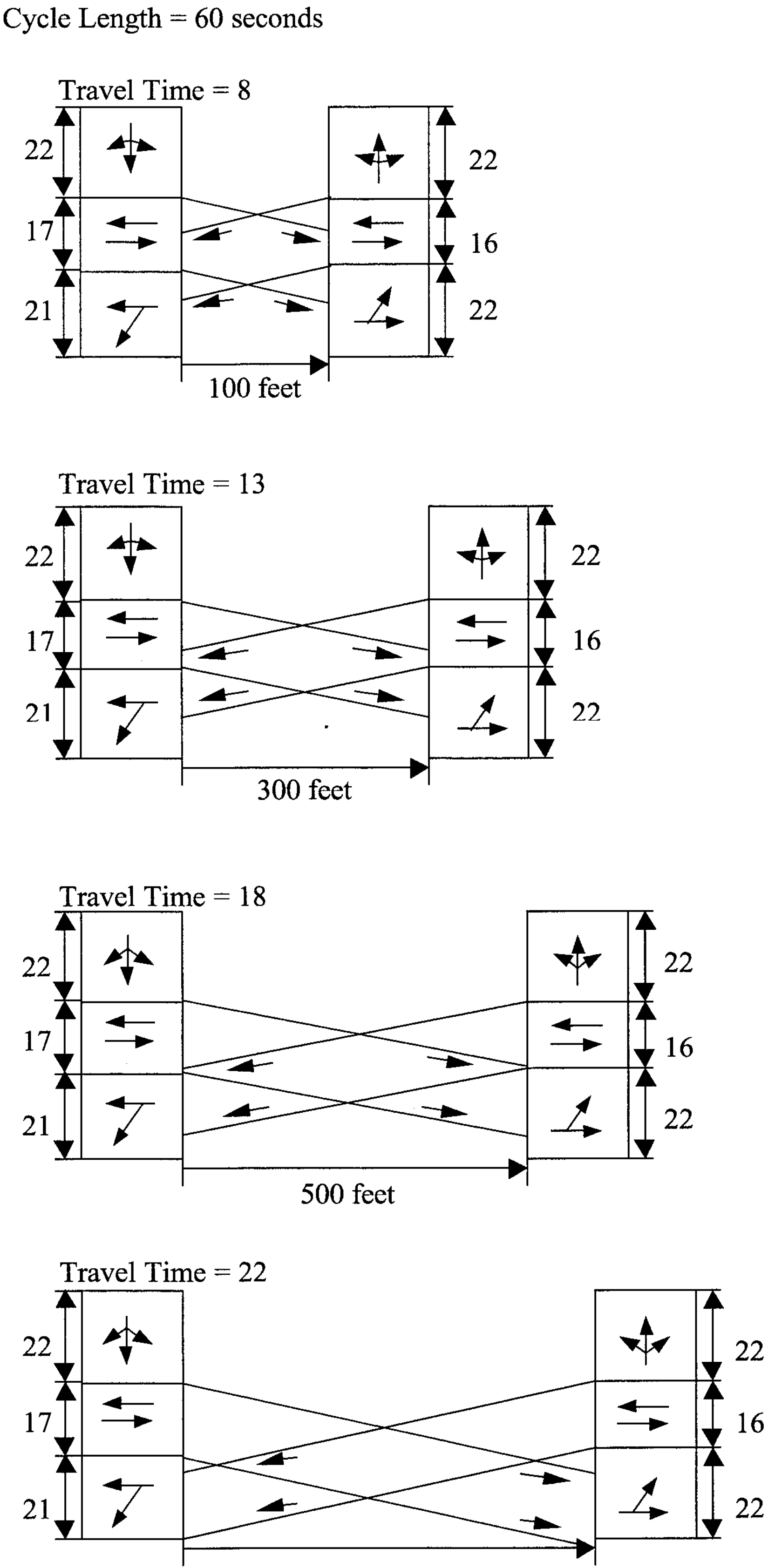


Figure 7. Effects of Link Distances on the Performance of Three-Phase Diamonds.

So far, our analysis shows that the wider the distance, the better the performance of the Texas three-phase strategy, as long as the demand at both frontage roads is balanced. When there is a significant imbalance in frontage road demands, this strategy causes a loss in capacity for the intersection with less frontage road demand. In those cases, a feature called "Conditional Service," available in most modern traffic controllers, can be used to provide unused green time from the frontage road phase to the interior left-turn phase for the same signal. These findings support previous research and experiences of engineers in Texas that Texas three-phase strategy works best when the distance between the two intersections of a diamond interchange is between 400 to 800 feet. However, this analysis will not be complete without discussing the effects of cycle length variation on the performance of this strategy, which will be discussed next.

Figure 8 shows how variations in cycle length affect the efficiency of Texas three-phase operation. In this analysis, we use the 500 feet scenario discussed above. For this scenario, a cycle length of 60 seconds provides the best progression. As can be observed from Figure 8, using a cycle length of 40 seconds will cause almost 50 percent of the arterial traffic to arrive at the downstream signal after it has turned red. However, the progression for frontage road traffic improves. Comparing the results for the 40 and 60 second cycle lengths (Figures 8 and 7), one can see that a cycle length of 55 seconds will result in a better timing plan by reducing the wasted time at the end of through platoons. The reader can also observe that an increase in the cycle length beyond 60 seconds increases delay for the left-turn traffic, especially for any U-turn traffic.

In summary, we recommend that Texas three-phase operation be used only when there is sufficient space (more than 500 feet) within the interchange to store vehicles. Also, selecting an optimum cycle length is key to the success of this strategy. For interior distance shorter than 500 feet, this strategy can be used for light to moderate traffic conditions if an interchange has U-turn bays and full left-turn lanes.

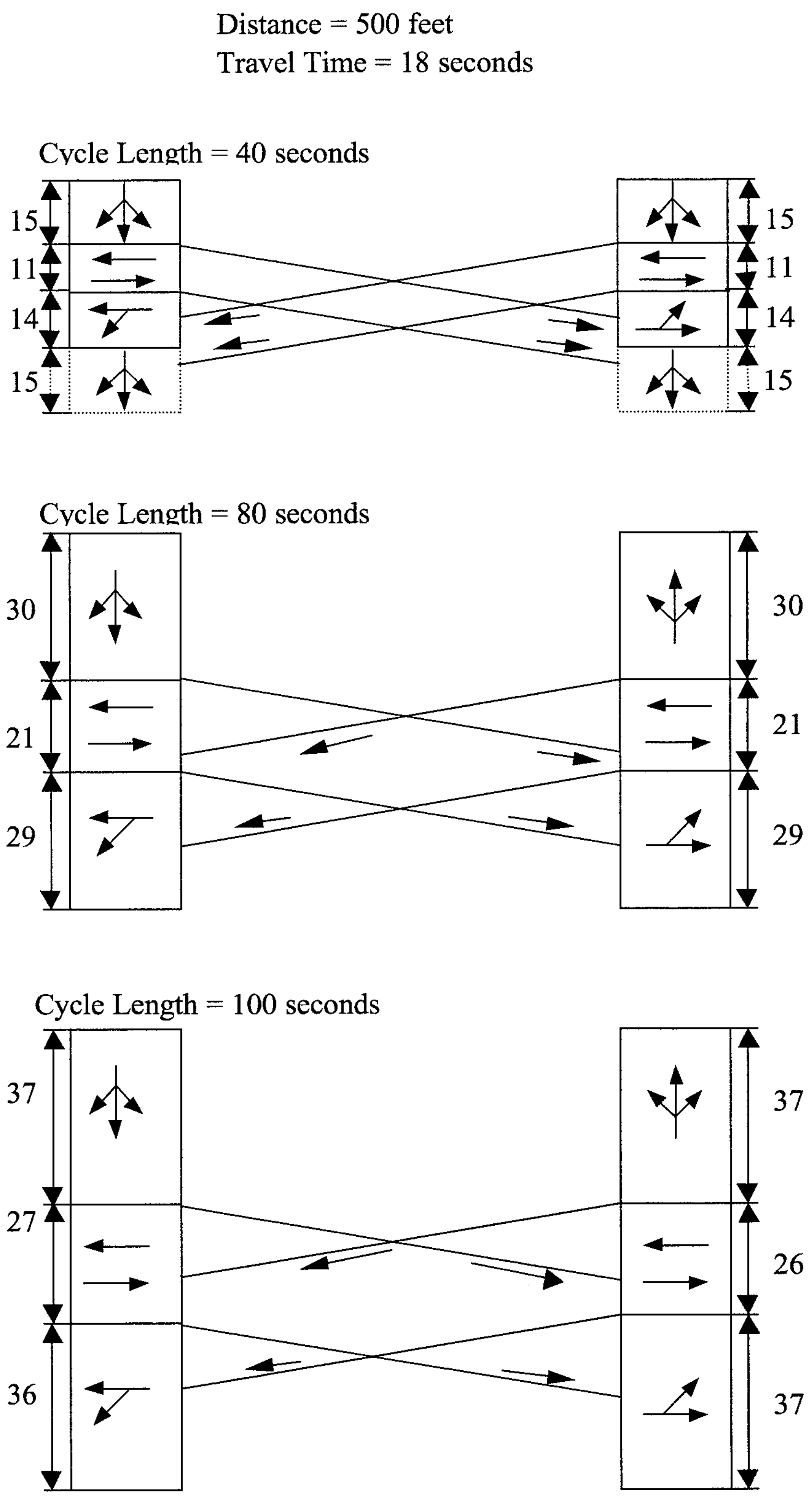
TTI Four-Phase Strategy

TTI four-phase operation uses lead-lead phasing and staggers the interior left turn movements. The basic objective of this strategy is to coordinate the two signals of the diamond interchange for providing through progression at the downstream signal. To achieve this objective, this strategy simultaneously calculates green splits and internal offsets. Thus, the calculation process treats the two intersections as one system and in doing so, takes into consideration the interior travel times. The green split calculation is as follows.

$$\begin{aligned} Let\ \ &\phi_1 + \phi_5 = C - \Phi \\ &\phi_2 + \phi_4 + \phi_6 + \phi_8 = C + \Phi \end{aligned}$$

where

$$\begin{aligned} \Phi &= \Phi_{LR} + \Phi_{RL} \\ &= \text{Travel Time From Left to Right} - 2\text{ sec.} + \text{Travel Time from Right to Left} - 2\text{ sec.} \\ &= \text{Travel Time From Left to Right} + \text{Travel Time from Right to Left} - 4\text{ sec.} \end{aligned}$$



Distance = 500 feet
Travel Time = 18 seconds

Cycle Length = 40 seconds

Cycle Length = 80 seconds

Cycle Length = 100 seconds

Figure 8. Effects of Cycle Length on the Performance of Three-Phase Diamonds.

For the TTI four-phase strategy, the basic rule for coordinating multiple signals, a requirement that cycle length be the same for all signals, remains unchanged for the pair of signals. A careful look at the above equations reveals that as the distance between the two signals increases (that is, travel time increases), the total green split for interior movements reduces, while the total green split for exterior movement increases. Also, the cycle length must be significantly larger than the total travel time in order to provide reasonable capacity. Because of the close proximity of the two intersections, travel time from one intersection to the next must take into consideration the fact that vehicles stopped at an exterior approach (usually the through vehicles) accelerate as they are traveling toward the next signal. The travel time will depend on two conditions:

1. vehicle is still accelerating when it reaches the downstream signal, and
2. vehicle achieves the design speed before it reaches the downstream signal. In this case the vehicle will cover the remaining distance to the downstream at design speed.

Figure 9 illustrates these two conditions for a design speed (*s*) of 35 mph. Note that the figure is a distance-versus-speed plot and consists of two regimes divided by the vertical dashed line. The left side describes the acceleration phase for a stopped vehicle until the vehicle achieves the design speed. The right side describes the constant speed motion of the vehicle once it achieves the design speed. In this example, the vertical dashed line represents the distance (*x*) the vehicle travels until it reaches the design speed (*s*). In this example the vehicle travels about 300 feet until it attains the design speed.

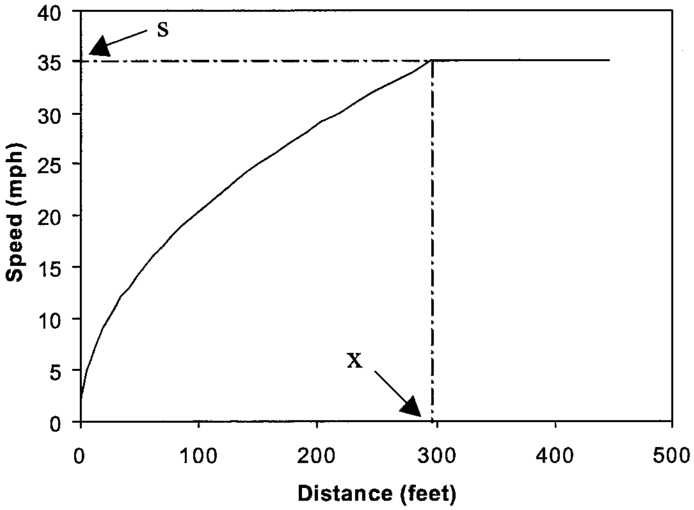


Figure 9. Acceleration Distance for a Given Design Speed.

Using this, we can calculate the time it will take for a vehicle, stopped at an exterior interchange approach, to travel to the next intersection for a given design speed (*s*), link distance (*d*), and acceleration. The first step is to calculate the distance needed for this vehicle to achieve the design speed. The second and final step is to calculate the travel time. The formulae are given below:

$$x = \frac{1}{2a} \times V_{\max}^2 \text{, where } V_{\max} = s \times \frac{5280}{3600}$$

$$\mathit{Travel\ Time} = \begin{cases} \sqrt{0.45 \times d + 0.5} & \mathit{if}\ d < x \\ \frac{1}{a} \times V_{\max} + 0.5 + \frac{d - x}{V_{\max}} & \mathit{otherwise} \end{cases}$$

It is a standard practice to use an acceleration rate of 4.44 ft/sec^2 for calculating travel times for use in diamond interchange analysis. We used this value and the above procedure to obtain travel times for a range of speeds and a range of link distances. Table 18 provides these values. For example, if the design speed and link-distance are 35 mph and 250 ft., respectively, the travel time will be 9 seconds.

Table 18. Travel-Time Table.

Design Speed (mph)	Link Distance (ft.)														
	100	150	200	250	300	350	400	450	500	550	600	650	700	750	800
20	5	7	9	10	12	14	16	17	19	21	22	24	26	28	29
25	5	7	8	9	11	12	13	15	16	18	19	20	22	23	24
30	5	7	8	9	10	11	13	14	15	16	17	18	19	20	22
35	5	7	8	9	10	11	12	13	14	15	16	17	18	19	20
40	5	7	8	9	10	11	12	13	14	14	15	16	17	18	19
45	5	7	8	9	10	11	12	13	14	14	15	16	17	17	18

Once the travel times for both directions, and thus the offsets, have been calculated, the phase times for exterior phases of a four-phase diamond can be calculated as follows:

$$\phi_i = \frac{y_i}{y_2 + y_4 + y_6 + y_8} \times (C + \Phi - 4l) + l \qquad \forall\, i = 2, 4, 6, 8$$

The final step is to calculate the times for the two interior left-turn movements using the following equations:

$$\phi_1 = \phi_6 + \phi_8 - \Phi$$
$$\phi_5 = \phi_2 + \phi_4 - \Phi$$

Since the above calculations of phase times guarantee through progression for any given distance, TTI four-phase operation minimizes the lengths of interior queues. Because of guaranteed through progression at the downstream signal, this strategy also conforms to drivers' expectancy. TTI four-phase is not flawless, however. Since the green time of interior left movements have a negative relationship with the overlap, the capacities of left-turn phases reduce with increasing distance. We will investigate the capacity versus link distance issue in the next chapter. Another drawback of this strategy is that all U-turn traffic gets stopped within the interchange. The easiest way to remedy this situation is to provide U-turn bays for sites with short spacing and heavy U-turn traffic. Based on engineers' experience, the TTI four-phase strategy works well for interchanges with widths less than 400 feet.

Figures 10 and 11 illustrate the effects of distance and cycle length variations on the performance of four-phase diamond interchanges. Since TTI four-phase calculates the phase times and progression simultaneously, unlike Texas three-phase, the timing plan will change as the interior distance changes. From Figure 10, one can see that all the main street traffic passes through the diamond without any interruption, whether it is through traffic or left-turn traffic. However, as described above, the interior green time will decrease as the link distance increases. In this case (cycle length of 60 seconds) TTI four-phase timing plans do not exist for link distances of 700 feet (overlap of 20 seconds) or more. This is because large overlaps either result in insufficient time for meeting minimum phase time requirements (assumed 10 seconds in our example), or reduce capacities of interior phases to zero. Thus, the shorter the link distance, the larger the interior capacity of a four-phase diamond-interchange.

Figure 11 shows the effects of cycle length variation on the performance of TTI four-phase operation. As can be seen, variations in cycle-length do not affect progression for the interior through movement. However, an increase in cycle length provides more green time and because of this, provides slightly better interior progression for U-turn traffic. The negative effect of larger cycle lengths, however, would be an increase in the sizes of queues and larger delays at exterior approaches and larger interior delays for U-turn traffic. The additional cost of increased delay and queue lengths outweigh any benefit resulting from slight improvement in the progression of U-turn traffic. Therefore, large cycle lengths should be avoided.

Extended Three-Phase Strategy

This method of operation treats the two intersections of a diamond independently. The green splits for use with this strategy are calculated for each intersection as follows:

$$\phi_i = \frac{y_i}{y_1 + y_2 + y_4} \times (C - 3l) + l \qquad \forall i = 1, 2, 4$$

$$\phi_i = \frac{y_i}{y_5 + y_6 + y_8} \times (C - 3l) + l \qquad \forall i = 5, 6, 8$$

In traditional implementations, each intersection requires a separate controller, as for a normal arterial with two traffic signals. The coordination between the two intersections is established by interconnecting the two controllers and specifying an offset relationship between them. The option of using two controllers provides the maximum flexibility because it allows the use of all four phasing patterns for the pair of intersections.

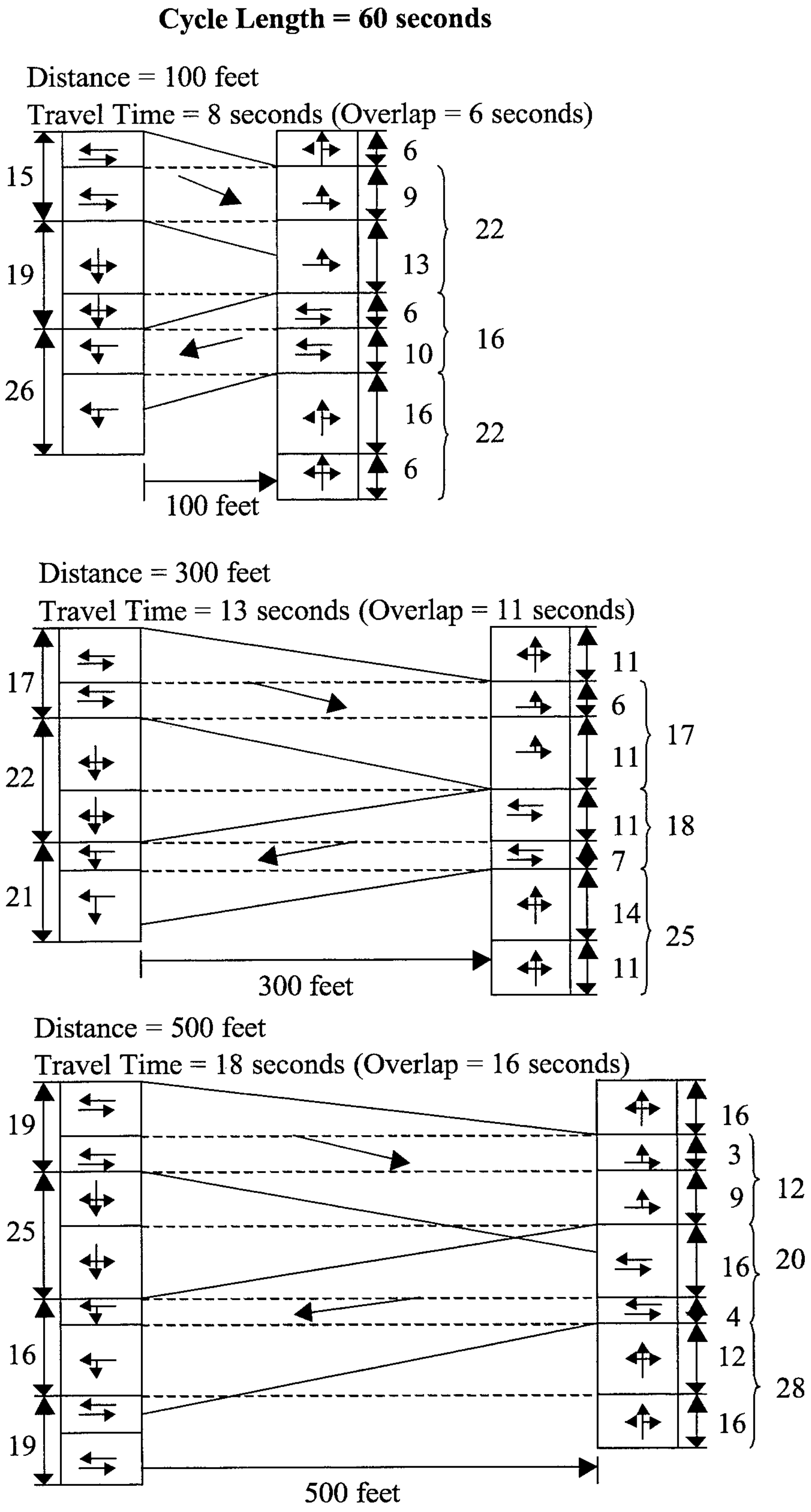
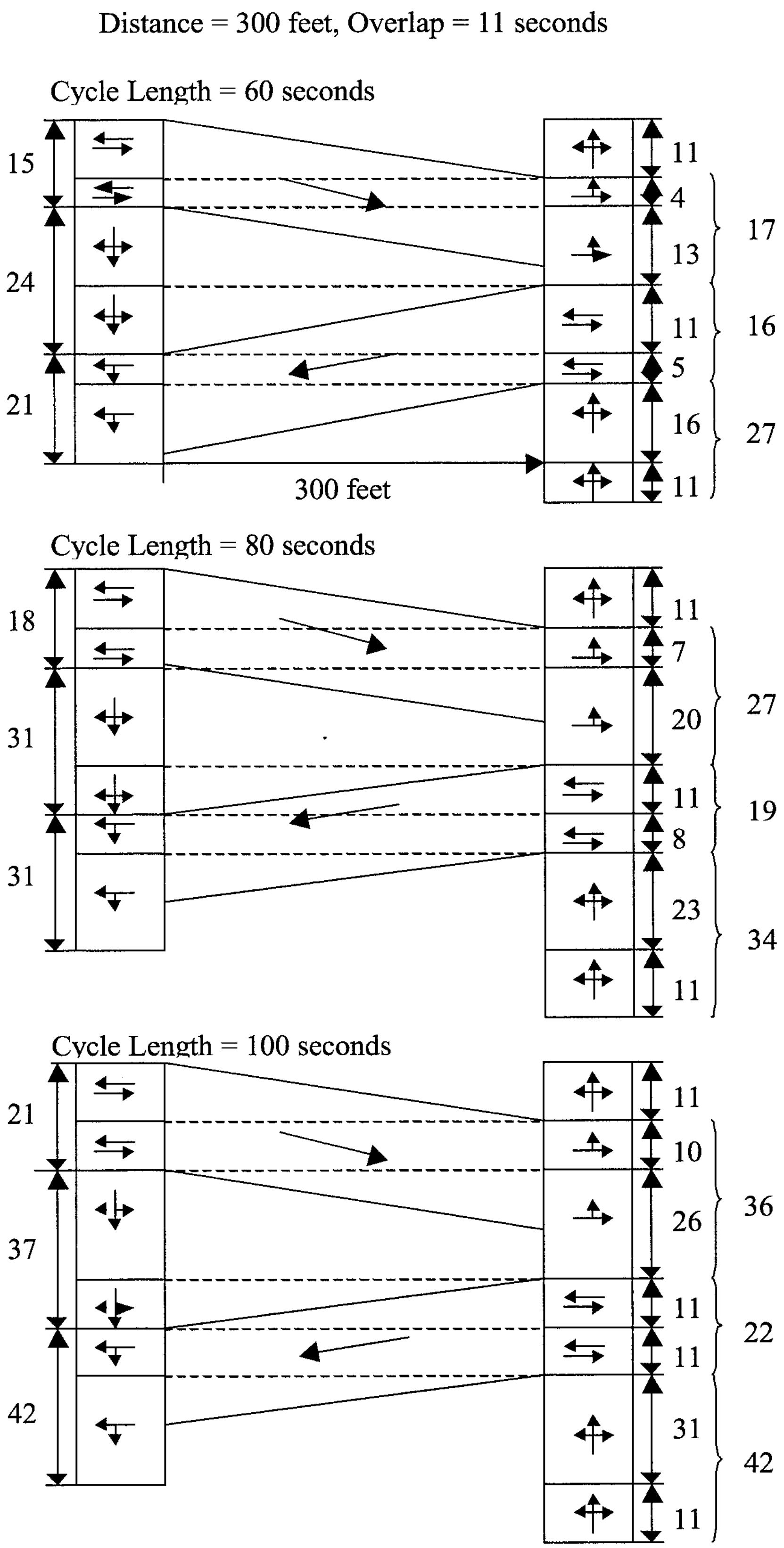


Figure 10. Effects of Distance on the Performance of Four-Phase Diamonds.


Distance = 300 feet, Overlap = 11 seconds

Cycle Length = 60 seconds

Cycle Length = 80 seconds

Cycle Length = 100 seconds

Figure 11. Effects of Cycle Length Variation on the Performance of Four-Phase Diamonds.

Most modern controllers used in Texas are capable of implementing this strategy using a single controller. The user can select one of two possible ways to implement this strategy with a single controller. The first implementation method is through the separate intersection control feature of Texas diamond controllers. With this preprogrammed option, the controller uses two rings (one for each intersection) and allows the user to define an offset relationship (called ring-lag) for the two signals. This mode, however, only allows the use of lead-lead phase sequence. The other, more cumbersome, method is to implement separate intersection control outside the diamond mode and requires defining the needed ring structure to achieve this objective. Engineers commonly use this strategy for conventional diamond interchanges (interchanges with 800 ft. or larger link distances). This strategy provides the maximum capacity when sufficient storage space exists. Further description of this strategy is beyond the scope of this project. However, in the next section, we use the capacity of extended three-phase operation as a benchmark for analyzing the capacity of the three-phase and four-phase strategies described earlier.

Simulation Studies of Control Strategies

This section presents results of studies conducted by researchers using CORSIM and PASSER III-90. For this analysis, we considered two control strategies, three interchange spacings, four volume conditions, and two volume distributions. This resulted in a total of 612 cases. We conducted 10 replications of one-hour simulation for each case. For brevity, we only present a summary of our findings.

- For 200 and 400 foot spacings, TTI four-phase strategy results in considerably lower delay than the Texas three-phase strategy. The delays for these strategies are similar for a spacing of 600 feet. For TTI four-phase, the internal delay increase as internal space increases. For Texas three-phase, internal delays decrease as spacing increases. The external delays for TTI four-phase were higher than the corresponding Texas three-phase delays for all conditions.
- For the light volume conditions, PASSER III-90 results compare well with the corresponding CORSIM results. Comparisons for higher volume conditions show significant difference in the delays. These trends are similar for both balanced and unbalanced scenarios. Considering the fact that PASSER III was developed for undersaturated conditions, these differences are to be expected.
- For 200 feet spacing and balanced scenario, TTI four-phase consistently produces lower delays than Texas three-Phase for the internal movements and consistently results in higher delays for the external movements. For 400 feet spacing, researchers observed similar trends for cycle lengths greater than 70 seconds. For some of the volume conditions and lower cycle lengths, Texas three-phase showed lower delays than TTI four-phase. This is because TTI four-phase does not have sufficient internal capacity at low cycle lengths. The external delays for TTI four-phase were higher for all cycle length and volume conditions studied. The trends for 600-foot spacing were similar to the 400-foot spacing trends in that TTI four-phase resulted in higher delays than the Texas three-phase delays for low cycle lengths. Also, the external delays were much higher for TTI four-phase timing plan.

- The unbalanced scenarios studied by the researchers included low volumes for the left intersection and a range of volumes for the right intersection. An increase in volumes at the right intersection showed that there is a corresponding increase in delays for the Texas three-phase strategy. For the TTI four-phase scenarios, the delays increased with cycle length to an extent (about 90 second cycle length) and then decreased for the intersection with higher internal volumes. TTI four-phase tends to give a greater proportion of the cycle length to the internal greens as the cycle length increases; this causes a decrease in the greens of the external movements feeding this internal movement, thus reducing the overall internal delays.
- For both balanced and unbalanced scenarios, the internal delays for a TTI four-phase timing plan become more uniform as the volumes increase. This is due to the metering of traffic. Traffic that could enter the interchange is metered such that all the traffic that gets into the interchange leaves without much queuing (except for U-turning vehicles). This allows the interchange interior to remain clear at the end of each cycle.
- An important factor to consider in selecting a timing plan during oversaturated conditions is the relative importance of the competing movements. From the studies, researchers observed that TTI four-phase kept the internals clear at all volume conditions (except for low cycle lengths), but this feature comes at the cost of the external movements. Depending on volume conditions and the exit ramp length, TTI four-phase could lead to blocking at the exit ramps. This should be considered before selecting a timing plan.
- Although PASSER III delays were significantly different for higher volume conditions, researchers found good correlation between PASSER III and CORSIM results.

THROUGHPUT CAPACITY OF INTERCHANGES

In the previous section, we provided an analysis of commonly used strategies for timing diamond interchanges. That analysis helped in understanding the operational characteristics of these strategies. The analysis also explained the basis for the following well-established guidelines and practices:

1. Use Texas three-phase strategy for compressed diamond interchanges.
2. Use TTI four-phase strategy for tight diamond interchanges.
3. Use extended three-phase strategy for conventional diamond interchanges.

The analysis presented earlier also pointed to the fact that the effectiveness of diamond interchange control strategies, especially TTI four-phase control, greatly depends on the cycle length. In this section, we develop a simple mathematical programming based methodology that will enable an engineer to make better cycle length selection for a range of prevalent traffic patterns. Given a geometric scenario, a selected control strategy, and volume counts, this methodology calculates maximum throughput capacity of an interchange. We define maximum throughput capacity of an interchange to be the total number of vehicles than can enter and leave the interchange without causing any internal queues.

Mathematical Formulation

In this section, we present a linear program (LP) describing the interchange throughput capacity. To keep this presentation simple, we have deliberately chosen to omit the derivation of this formulation. In concept, this LP is similar to the LP proposed by Wattleworth in 1972 (*41*); however, it is much simpler in that it does not require the use of an LP algorithm or software for solving the capacity problem. Furthermore, we make the following assumptions:

1. the origin-destination of traffic flow stays constant for a given analysis period,
2. no blocking (queue spill-back) occurs in the interior of the interchange,
3. ideal saturation flow rates are known, or can be calculated, for each movement, and
4. traffic control strategy, and therefore, the cycle length and green splits are known.

The second assumption is to ensure that all traffic entering the diamond interchange during one cycle is able to leave the interchange during the same or next cycle. We achieve this by maintaining an operational capacity for each interior movement less-than-or-equal to 95 percent of ideal capacity for that movement. Then, the throughput capacity of the interchange, in vehicles per hour (vph), will be equal to the sum of vehicles entering the interchange or the sum of vehicles leaving the interchange. The LP formulation is as follows:

Maximize: V

Subject to:

$$V \le \frac{g_i \times s_i}{C} \times \frac{1}{p_i} \qquad \forall i \in E$$

$$V \le 0.95 \times \frac{g_i \times s_i}{C} \times \frac{1}{p_i} \qquad \forall i \in I$$

Where:

C: cycle length, seconds
V: hourly flow rate (demand) for the system, vph
g_i: effective green time of i^{th} movement per cycle, seconds
s_i: hourly saturation flow of i^{th} movement, vph
E: set of exterior movements (left-, through- and right-movements at each frontage road, and through and right movements at each artery approach)
I: set of interior movements (interior left and through movements)
p_i: ratio of volume for approach i to sum of exterior volumes

The reader can verify that the above formulation contains one variable and 14 constraints. Furthermore, the constraint with the smallest right-hand-side will dictate the system throughput capacity. Therefore, all one needs to do to get a solution is to:

- calculate the ideal saturation flow rate for each movement,
- calculate the green splits for the selected control strategy and selected cycle length,
- calculate the movement-volume to total-interchange-volume ratio for each movement,
- calculate the right-hand-side constant for each constraint, and
- select the constraint with the smallest right hand side constant.

The selected constraint identifies the bottleneck movement, and its right-hand-side constant is equal to the interchange throughput capacity. The reader should note that it is possible for more than one movement to be a bottleneck. This happens when the right-hand sides of more than one constraint are equal to the smallest value. The procedure described above can be used to obtain the capacity of an interchange control strategy for a given geometric scenario and range of cycle lengths. In addition, the same procedure can be used to compare various control strategies. In the next section, we use synthetic data to compare various diamond control strategies under different origin-destination scenarios. Also, we provide and example set of calculations to illustrate the use of LP presented above.

Example of Capacity Calculations

In this section, we show how to calculate the throughput capacity using the procedure described in the previous subsection. Here, we assume TTI four-phase operation, an interchange with 200 foot spacing, and a cycle length of 70 seconds. The total interchange demand is assumed to be 1400 vph. Total interchange demand is the sum of all exterior movement (arterial through and frontage road left turns) volumes entering the interchange. For operational analysis, one will obtain these volumes through field studies. Tables 19 and 20 provide the data assumed or calculated for illustration purposes. In the headings of these tables, a number followed by a letter (e.g., 2T, 4L, 4R, etc.) identifies NEMA phase number and movement (left, through, or right) for that phase. The first line provides the volume data. The second line of data provides the ratio of each volume to the total interchange demand at the exterior movements (1400 vph). For instance, the ratio for the arterial through movement (2T) at the left intersection is 0.3571 (shown in Table 19 using bold font), which can be obtained by dividing 500 by 1400. The last two lines provide the saturation flow rates and effective green times (split minus lost time) for each movement.

Table 19. Data for Left Signal of the Interchange.

	Arterial		Frontage			Interior	
	Through (2T)	Right (2R)	Left (4L)	Through (4T)	Right (4R)	Left (1L)	Through (1T)
Volume	500	50	200	100	50	200	500
Volume as Fraction	**0.3571**	0.0357	0.1429	0.0714	0.0357	0.1429	0.3571
Saturation Flow	5000	500	1770	2346	1173	1770	3725
Effective Green	17	17	19	19	19	22	43

Table 20. Data for Right Signal of the Interchange.

	Arterial		Frontage			Interior	
	Through (6T)	Right (6R)	Left (8L)	Through (8T)	Right (8R)	Left (5L)	Through (5T)
Volume	500	50	200	100	50	200	500
Volume as Fraction	0.3571	0.0357	0.1429	0.0714	0.0357	0.1429	0.3571
Saturation Flow	5000	500	1770	2346	1173	1770	3725
Effective Green	17	17	19	19	19	22	43

The above tables have all the information we need to calculate the right-hand-sides (RHS) of capacity constraints for each movement. We illustrate these calculations below for left and right signals of the interchange:

Left Signal:

$$V \leq \frac{g_{2T} \times s_{2T}}{C} \times \frac{1}{p_{2T}} = \frac{17 \times 5000}{70} \times \frac{1}{0.3571} = 3400$$

$$V \leq \frac{g_{2R} \times s_{2R}}{C} \times \frac{1}{p_{2R}} = \frac{17 \times 500}{70} \times \frac{1}{0.0357} = 3400$$

$$V \leq \frac{g_{4L} \times s_{4L}}{C} \times \frac{1}{p_{4L}} = \frac{19 \times 1770}{70} \times \frac{1}{0.1429} = \boldsymbol{3362}$$

$$V \leq \frac{g_{4T} \times s_{4T}}{C} \times \frac{1}{p_{4T}} = \frac{19 \times 2346}{70} \times \frac{1}{0.0714} = 8918$$

$$V \leq \frac{g_{4R} \times s_{4R}}{C} \times \frac{1}{p_{4R}} = \frac{19 \times 1173}{70} \times \frac{1}{0.0357} = 8918$$

$$V \leq 0.95 \times \frac{g_{1L} \times s_{1L}}{C} \times \frac{1}{p_{1L}} = 0.95 \times \frac{22 \times 1770}{70} \times \frac{1}{0.1429} = 3698$$

$$V \leq 0.95 \times \frac{g_{1T} \times s_{1T}}{C} \times \frac{1}{p_{1T}} = 0.95 \times \frac{43 \times 3725}{70} \times \frac{1}{0.3571} = 6087$$

Right Signal:

$$V \leq \frac{g_{6T} \times s_{6T}}{C} \times \frac{1}{p_{6T}} = \frac{17 \times 5000}{70} \times \frac{1}{0.3571} = 3400$$

$$V \leq \frac{g_{6R} \times s_{6R}}{C} \times \frac{1}{p_{6R}} = \frac{17 \times 500}{70} \times \frac{1}{0.0357} = 3400$$

$$V \leq \frac{g_{8L} \times s_{8L}}{C} \times \frac{1}{p_{8L}} = \frac{19 \times 1770}{70} \times \frac{1}{0.1429} = \boldsymbol{3362}$$

$$V \leq \frac{g_{8T} \times s_{8T}}{C} \times \frac{1}{p_{8T}} = \frac{19 \times 2346}{70} \times \frac{1}{0.0714} = 8918$$

$$V \leq \frac{g_{8R} \times s_{8R}}{C} \times \frac{1}{p_{8R}} = \frac{19 \times 1173}{70} \times \frac{1}{0.0357} = 8918$$

$$V \leq 0.95 \times \frac{g_{5L} \times s_{5L}}{C} \times \frac{1}{p_{5L}} = 0.95 \times \frac{22 \times 1770}{70} \times \frac{1}{0.1429} = 3698$$

$$V \leq 0.95 \times \frac{g_{5T} \times s_{5T}}{C} \times \frac{1}{p_{5T}} = 0.95 \times \frac{43 \times 3725}{70} \times \frac{1}{0.3571} = 6087$$

From the above calculation, we see that the smallest RHS is 3362 (identified using bold font), corresponding to left-turn movements from the two frontage roads. Thus, the interchange throughput capacity is 3362 vph. In this case however, the demand (1400 vph) is well below the interchange capacity. Theoretically, the interchange throughput capacity can be increased by increasing the capacity of the frontage road left-turn movements (by changing lane assignments or reallocating the phase times) or by reducing demand. Since our example network did not have U-turn lanes, adding these lanes will reduce left-turn demand for this case.

Before proceeding, it is appropriate to offer some additional comments regarding the use of the above procedure using data collected in the field. Due to errors in data collection, the sum of exterior volumes (frontage road left and arterial through) from one intersection may not be equal to the sum of interior volumes (left and through) at the downstream signal. However, since our analysis assumes input-output balance, one must normalize the volumes for the interior movements as follows:

1. Select an interior approach.
2. Find the sum of interior left-turn and through volumes for the selected interior approach.
3. Find the sum of exterior (frontage road left-turn and arterial through) volumes at the upstream signal feeding traffic to the interior approach selected in Step 1.
4. Divide the interior left-turn volume by the sum obtained in Step 2, and multiply this number by the sum obtained in Step 3 to obtain the normalized left-turn volume.
5. Divide the interior through volume by the sum obtained in Step 2, and multiply this number by the sum obtained in Step 3 to obtain the normalized through volume.
6. Repeat Steps 1 through 5 for the other interior approach.
7. Use the normalized volumes from Steps 4 and 5 in the capacity analysis procedure.

Comparison of Various Control Strategies

In this subsection, we use the previously developed technique (LP) to compare the capacity of various control strategies for a range of cycle lengths and traffic patterns. For the analysis present here, we use a diamond interchange with lane assignments shown in Figure 12. This interchange has no U-turn lane. It has full interior left-turn lanes. We use six different volume conditions derived from data described in Tables 19 and 20. Note that the example calculation illustrated in the previous subsection used the first volume scenario.

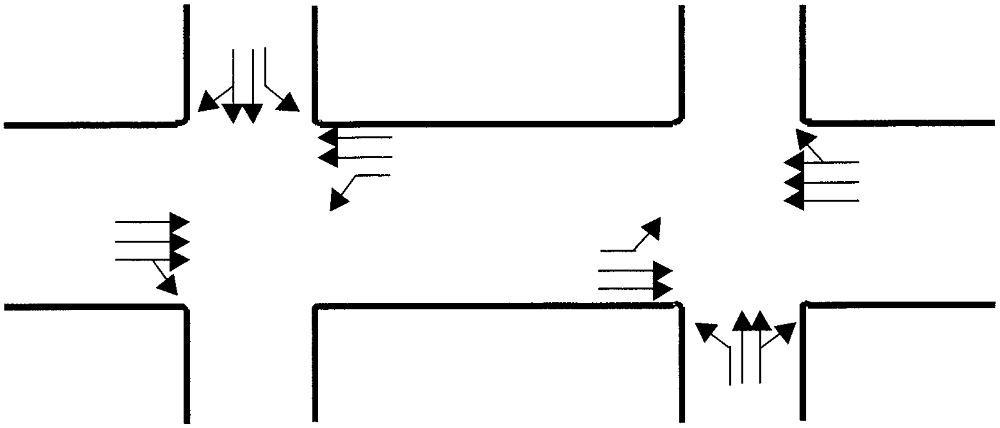


Figure 12. Number of Lanes and Lane Assignments for Test Scenario.

Table 21. Base Volume Conditions.

	Arterial		Frontage Road		
	Through	Right	Left	Through	Right
Light Traffic	500	50	200	100	50
Heavy Traffic	1000	50	900	100	50

Table 22. Interior Left and Through Traffic as Percent of Exterior Movements.

	From Arterial		From Frontage Road	
	Left (%)	Through (%)	Left (%)	Through (%)
Light Traffic	30	70	25	75
Heavy Traffic	20	80	28	72

Balanced Light Traffic on All Exterior Approaches

In this example we assume light traffic conditions at all four exterior approaches to the diamond interchange. Furthermore, we assume equal demand for the two arterial approaches and equal demand for the two frontage road approaches. The total interchange demand for this case is 1400 vph. Figure 13 provides the analysis results.

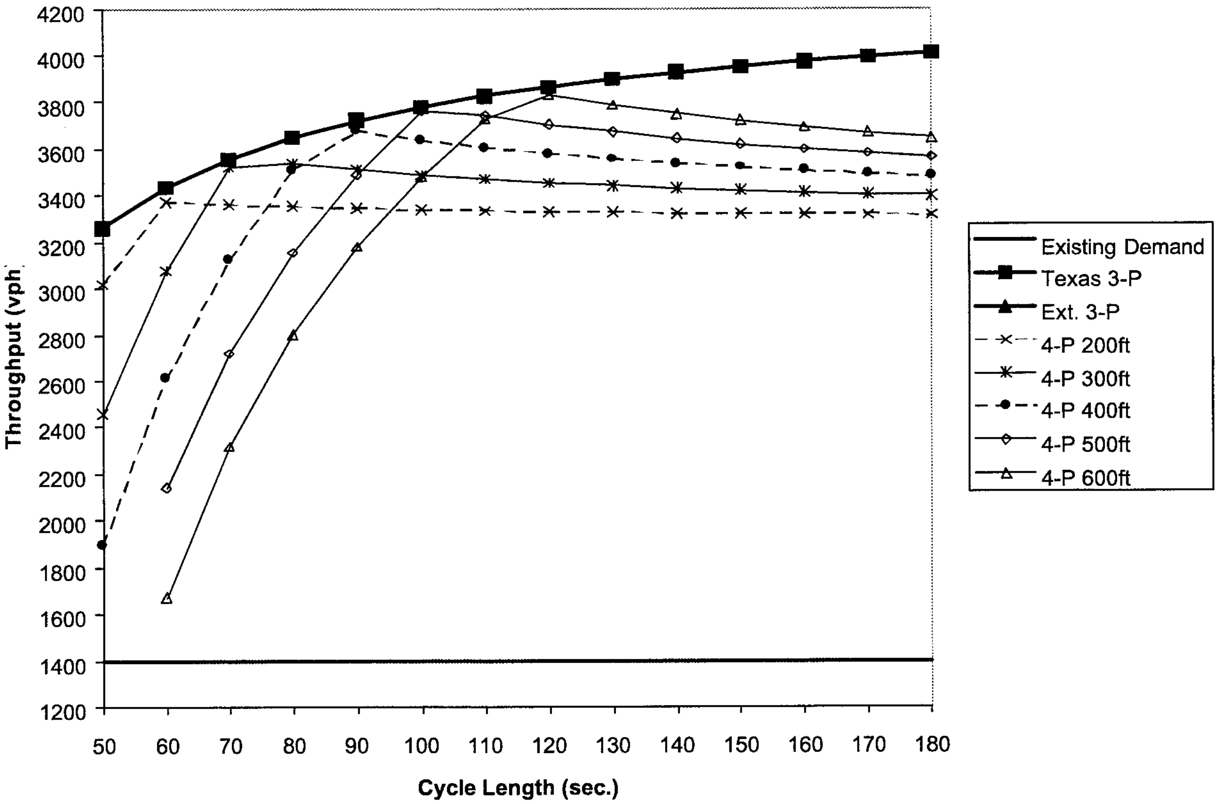


Figure 13. Interchange Throughput Capacities for Balanced Light Demand Case.

Figure 13 provides throughput capacity of three control strategies for a range of cycle lengths and signal spacing. The horizontal line at the bottom identifies the current demand level for the interchange and shows that all options have more capacity than demand. We obtain the following observations about throughput capacity from the graph:

- The throughput capacities for Texas three-phase and extended three-phase operations are identical and increase with cycle length. These capacities are also higher than the capacities for all TTI four-phase cases. In reality, this will only be true when there is sufficient storage space and when no blocking occurs.
- The capacity of a TTI four-phase operation increases sharply with an increase in cycle length until it reaches the capacity of the three-phase operation. The capacity decreases for cycle length increase beyond this point.
- For TTI four-phase operation, larger interior spacing requires larger cycle length to achieve optimum capacity. Furthermore, the optimum capacity for TTI four-phase increases with an increase in interior spacing.

Balanced Traffic with Light Arterial Demand and Heavy Frontage Road Demand

Figure 14 shows the results of this analysis. Note that the interchange traffic demand in this case is twice that for the case presented in the previous subsection.

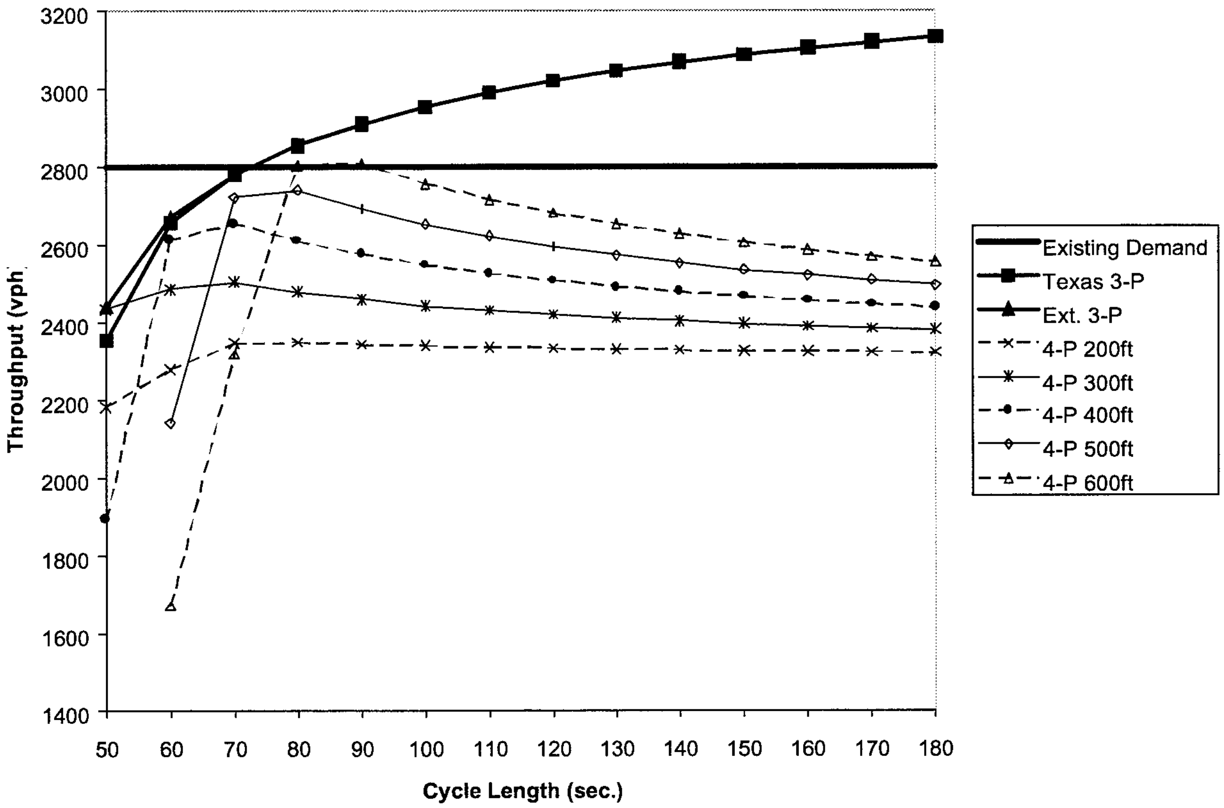


Figure 14. Balanced Traffic with Light Arterial and Heavy Frontage Road Demand.

All observations from the previous case apply here as well, except that the capacities of TTI four-phase operations for all interchange spacings are slightly below the capacity for three-phase operations. Also, a diamond interchange with 600 feet spacing is the only interchange that has sufficient capacity to handle the demand. In this case, the bottlenecks are the capacities of frontage road left-turn movements. With this pattern of demand, one has the following options:

- Use one of the two three-phase strategies when the interior distance is 400 feet or more. For distances less than 400 feet, these strategies will cause interior blocking, an effect not captured in the above analysis.
- Use TTI four-phase operation for interchange spacing of less than or equal to 400 feet. As shown previously, this operation minimizes internal blocking (which might only occur for U-turn traffic), and guarantees through progression at interior approaches.
- Make changes in frontage road lane assignments to increase the capacities of left-turn movements.
- Build U-turn lanes to reduce frontage road left-turn demand.

Balanced Traffic with Heavy Arterial Demand and Light Frontage Road Demand

Figure 15 shows the results for this case. In this case the interchange demand is 2400 vph, and all studied options provide sufficient capacity to handle this situation.

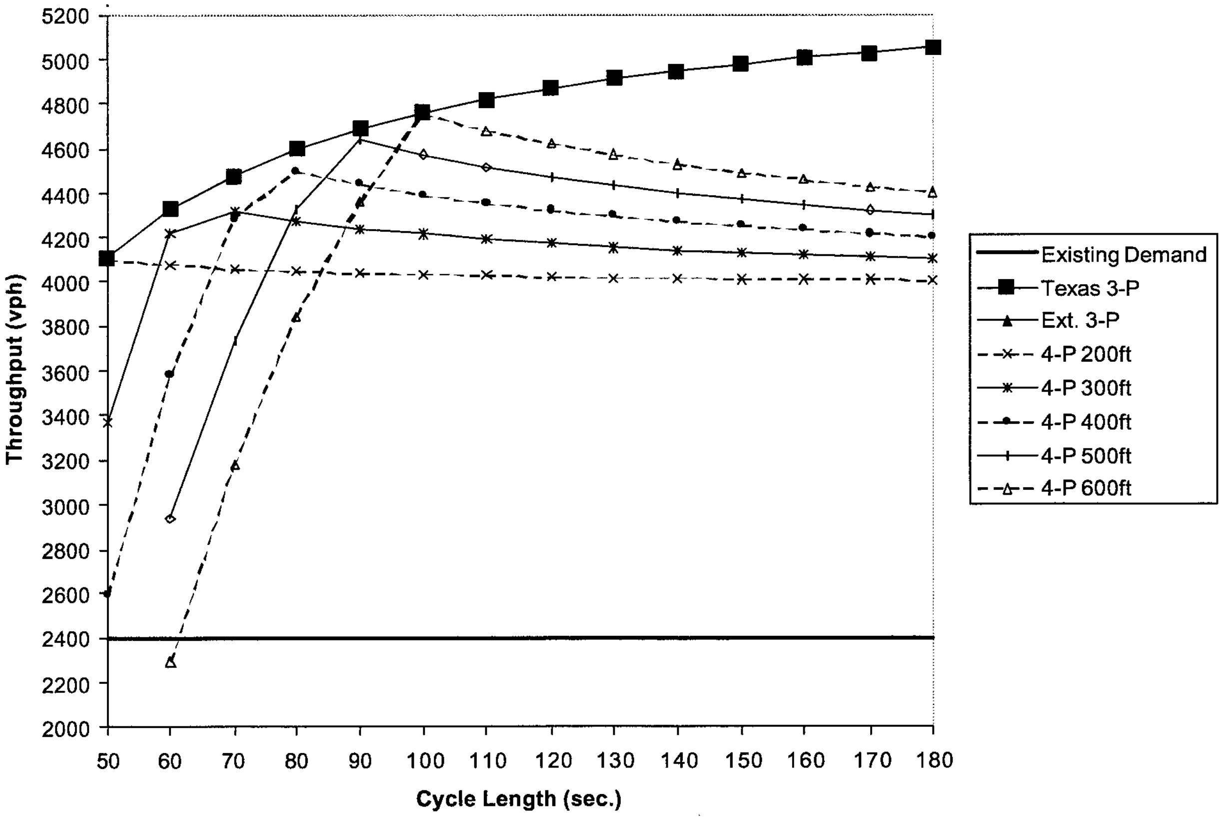


Figure 15. Balanced Traffic with Heavy Arterial Demand and Light Frontage Road Demand.

Balanced Light Traffic on Arterial and Heavy Traffic on Left Frontage Road

Figure 16 shows the results of this analysis. Here we used heavy traffic conditions on the left frontage road and light traffic conditions on the right frontage road. The following observations can be made about this traffic pattern:

- As expected, there is a sharp decrease in the capacity of the Texas three-phase strategy. This strategy still provides sufficient capacity for cycle length of 80 seconds or higher.
- The extended three-phase strategy provides sufficient capacity even for a cycle length of 50 seconds.
- If one uses an optimal cycle length, TTI four-phase strategy provides sufficient capacity for all link-distances studied. Furthermore, the capacity of TTI four-phase strategy increases for larger cycle lengths, although this increase is marginal.

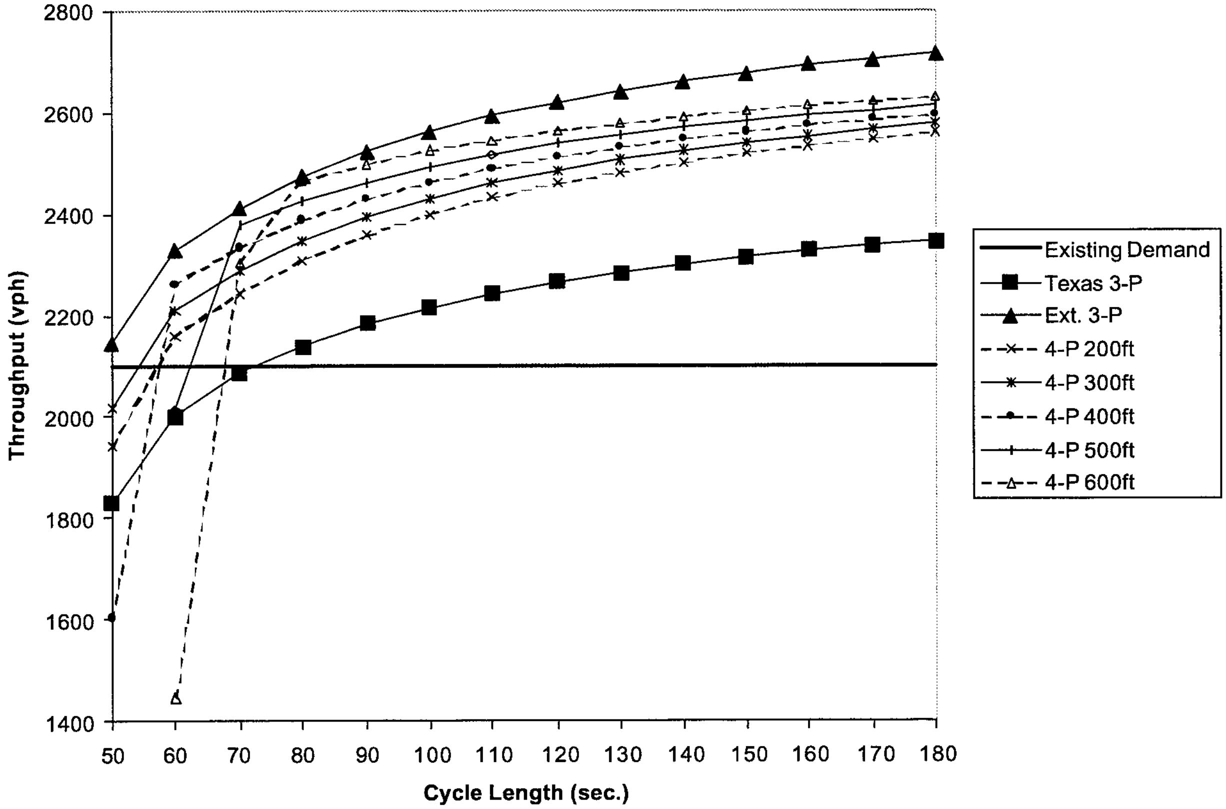


Figure 16. Balanced Light Traffic on Arterial and Heavy Traffic on One Frontage Road.

Heavy Traffic on the Left Intersection and Light Traffic on the Right Intersection

Figure 17 shows the results of this analysis. From this figure, the reader can see that the capacity of Texas three-phase strategy is much below what is need to handle the total traffic demand. The extended three-phase strategy has sufficient capacity when one uses a cycle length of 70 seconds or more. Furthermore, TTI four-phase has sufficient capacity for all link distances when one uses a cycle length of 100 seconds or more. Under this type of traffic pattern, Texas three-phase operation should not be used. Furthermore, distance criteria presented earlier should be used to select extended three-phase or TTI four-phase operation.

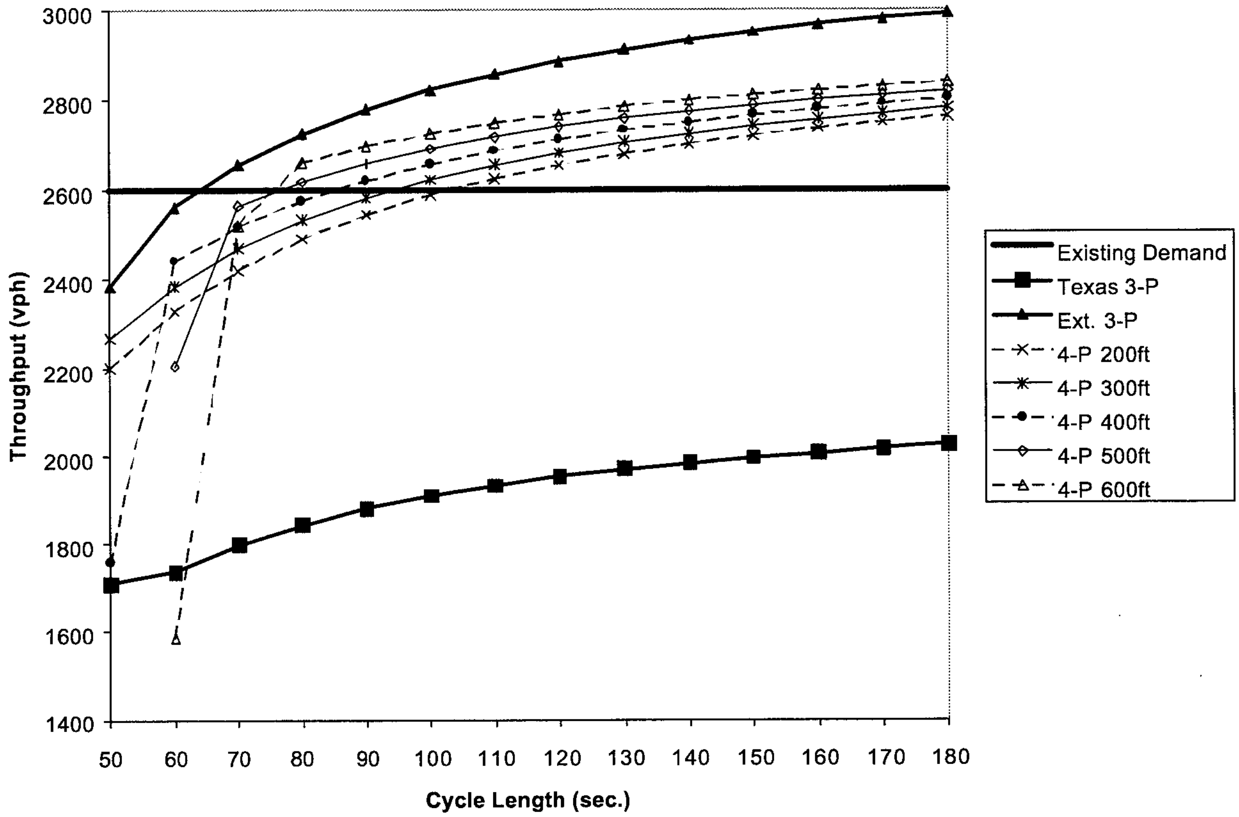


Figure 17. Heavy Demand at Left Signal and Light Traffic at Right Signal.

Heavy Arterial Demand on Left-Side and Light Demand on Other Approaches

Figure 18 shows the results of this scenario. As can be seen, the total demand is light as compared to the capacities of the three strategies studied. Also, the two three-phase strategies (Texas three-phase and extended three-phase) have identical capacities because of balanced demand on frontage roads.

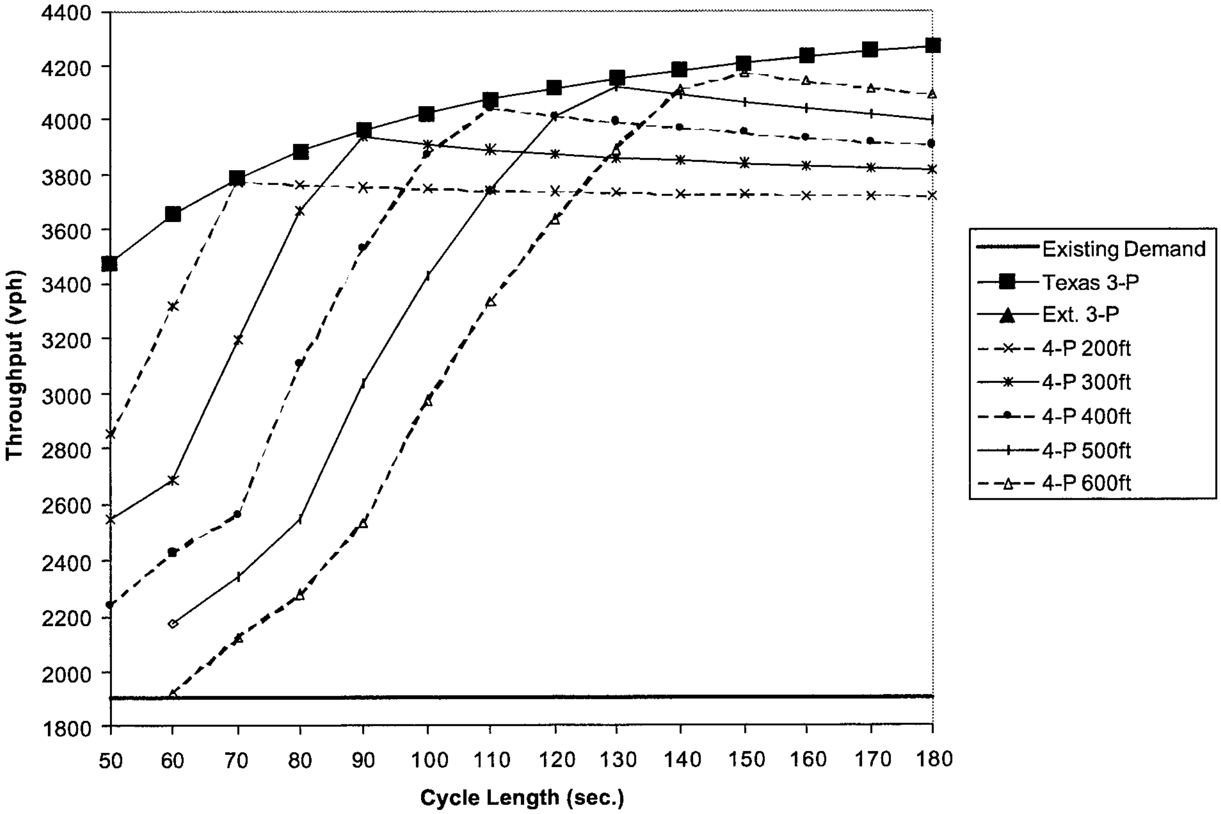


Figure 18. Heavy Demand at Left Arterial Approach and Light Demand at All Other Approaches.

Summary

In this section, we presented a procedure for estimating the capacity of a diamond interchange. This procedure is a useful tool for the analysis and timing of diamond interchanges when used in conjunction with the distance criteria established earlier in this chapter. We also showed the results of our capacity analysis techniques for one geometric scenario and a range of origin-destination patterns and different traffic demands. The graphs (six different patterns) provided above are not only useful for understanding the specific conditions studied, but can also be used by engineers to determine optimal cycle length for a given origin-destination scenario.

The best option is to use the detailed procedure for analyzing the capacity of the specific interchanges of concern; however, an analyst can use the capacity plots for six origin-destination patterns presented in this section. The following steps can be used if an analyst chooses to use these graphs:

- use distance criteria for selecting three-phase or four-phase operation,
- identify the traffic pattern and select the appropriate graph,
- determine the total interchange demand, and
- from the selected graph, determine the best cycle-length for calculated demand.

5. COORDINATION OF INTERCHANGES WITH ADJACENT SIGNALS

In the previous chapter, we presented a detailed analysis of standard strategies for operating diamond interchanges. We also presented a simple technique to analyze the throughput capacity of interchanges and provided guidelines for determining the best operation. In this chapter, we present procedures and guidelines for coordinating diamond interchanges with adjacent traffic signals located in close proximity to an interchange. For simplicity, we consider the case when there is only one adjacent intersection. The analysis of this chapter can be easily extended to the case when there are more signals. Besides, from the survey we conducted earlier, we found that the most common situations faced by engineers are isolated interchanges or those that have one adjacent signal.

PROBLEM DESCRIPTION AND NOTATION

Figure 19 illustrates the interchange plus adjacent signal case we use in this section. For this scenario, we use the letter "D" for diamond and the letter "S" for signal to label the NEMA movement numbers for the diamond interchange and the adjacent signal, respectively. In order to provide coordination, the interchange and the signal must be operated as one system with a common cycle length. Furthermore, the side of the interchange adjacent to the traffic signal now becomes an interior approach whose operation depends on the operation of the adjacent signal. Similarly, the eastbound approach to the adjacent signal is also an interior movement. Thus, this system has three external approaches to the interchange and three external approaches to the intersection.

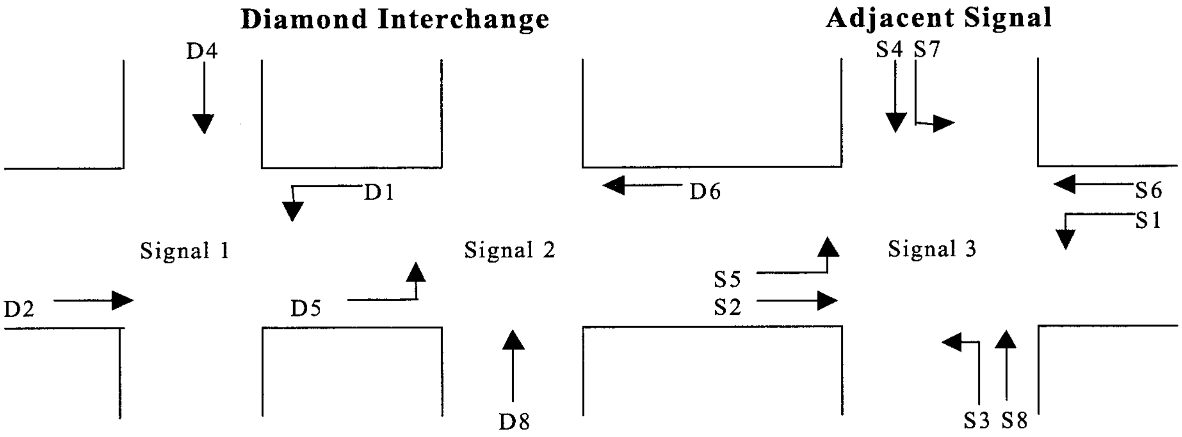


Figure 19. Diamond Interchange with an Adjacent Traffic Signal.

In addition, we use the following notation:

C: cycle length, in seconds
ϕ_{di}: phase time of movement i at the diamond interchange, in seconds
ϕ_{Si}: phase time of movement i of the adjacent signal, in seconds
Φ_d: total overlap (for four-phase diamond interchanges), seconds
Φ_S: sum of offsets between right signal of interchange and adjacent signal, in seconds
v_i: volumes for movement i, in vph
s_i: saturation flow rate for movement i, in vph
c_i: capacity of movement i, in vph

SYSTEM CAPCITY

The LP-based procedure presented in the previous section for analyzing the throughput capacity of interchanges can be extended for application to a system including a diamond interchange and any number of adjacent signals. For use in this analysis, we assume that phase times for the adjacent traffic signal will be calculated with the standard technique (Webster's method). Volumes collected in the field will have to be normalized for all internal approaches to the intersection. In the previous chapter, we formulated an LP to find the maximum throughput of a diamond interchange. The same LP formulation can also apply to the case of diamond interchange and adjacent signals. Figure 20 illustrates the capacity of a hypothetical diamond-interchange-plus one adjacent signal system.

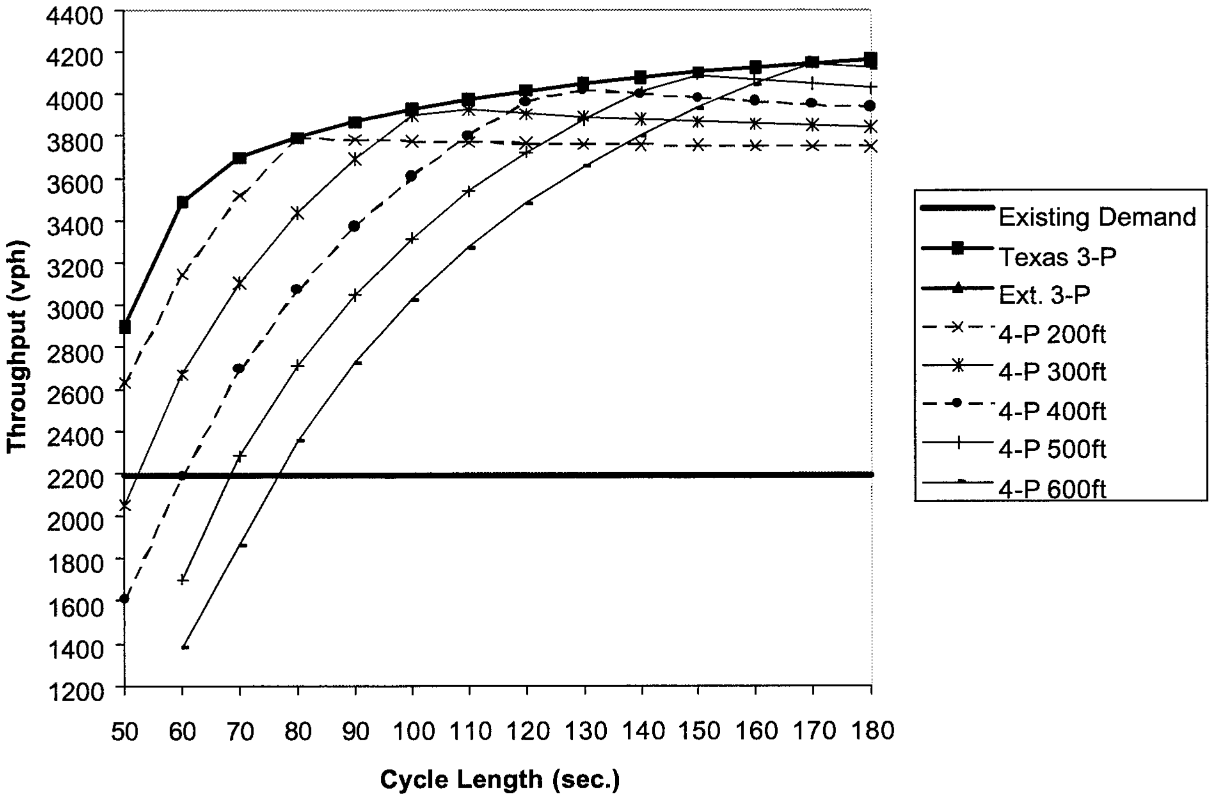


Figure 20. Sample Throughput Capacity Plot for a Diamond and Signal System.

The capacity analysis of the system does not depend on the distance between the diamond and the adjacent signal. However, this analysis can help in finding out if internal green times are sufficient to handle all external demand for the system. If the link between diamond interchange and adjacent signal link is known (either through capacity analysis or through field observations) to be undersaturated, the coordination guidelines of the next section apply. We will address the coordination of congested cases in a later section.

AN EASY APPROACH TO COORDINATION

In this section, we describe a simple approach to coordinating an interchange with adjacent signals on the arterial. The first step in establishing coordination is to analyze the operation of the diamond interchange to determine the appropriate strategy (three-phase or four-phase) and a range of cycle lengths. For this step, we recommend the procedures described in the previous chapter. If the best strategy for diamond happens to be one of the two three-phase strategies, we recommend using a program such as PASSER II or PASSER IV for coordinating the system. If TTI four-phase is the best strategy, we recommend the procedures described in this section.

Four-Phase Diamond and Adjacent Signal

We know from previous analysis and engineers' experience that TTI four-phase control guarantees progression for through traffic at interior approaches of the interchange. Thus, the objective of coordination for a four-phase diamond would be to provide progression for these vehicles through the adjacent traffic signal(s). A secondary objective is to provide progression for arterial traffic from the adjacent signal through the diamond interchange. The first step toward achieving this result is to find the travel times for the two directions linking the interchange and the adjacent signal. For future reference, we will use the term "interface-link" for the link between the interchange and the adjacent signal. In the previous chapter, we presented a method to determine travel time for use in timing diamond interchanges. The same procedure can be used to determine the travel times for the interface-link as follows:

- For the signal to interchange flow direction, use the stop-bar to stop-bar distance to calculate the time it will take for a stopped vehicle at the signal to accelerate and reach the diamond interchange.
- For the interchange to signal flow direction, the vehicles will be already moving when the interior phase at the diamond interchange turns green. In this case, the following steps will be needed to calculate the travel time:
  1. Calculate the interior travel time for the interchange.
  2. Calculate the travel time for a vehicle stopped at the exterior interchange approach to travel through the interior diamond link to the adjacent signal.
  3. Subtract the value obtained in Step 1 from that obtained in Step 2.

The desired offset in a travel direction is equal to the travel time for the associated direction. Whether one can obtain two-way progression for the interface link depends on travel times on the interface link, phase times at the right intersection of the diamond, and phase times and phase sequence at the adjacent signal. Figure 21 illustrates a subset of cases in which it is possible to achieve good two-way progression for a short interface-link.

The top part of Figure 21 illustrates the case when the arterial through phases ϕ_{S2} and ϕ_{S6} (phase for movements S2 and S6 in Figure 19) begin simultaneously. Two possible phasing sequences result in this situation. The first case is when both arterial left-turn phases (for movements S1 an S5 in Figure 19) lag. The other situation results when both left-turns phases lead but are of same duration. In this situation and in the absence of any queues at the interface-link, perfect two-way progression can be achieved by setting interior left-turn phase at the diamond interchange (ϕ_{d5}) equal to the sum of travel times (Φ_S) for the interface link. In the presence of queues, a situation that is normally true, one must adjust green splits and offsets to provide needed queue clearance time.

The middle part of Figure 21 illustrates the case when arterial left turns at the adjacent signal lead and when the phase for movement S2 is larger than the phase for movement S6. In this case, perfect two-way progression can be achieved by initially setting ϕ_{d5} equal to the sum of Φ_S and the overlap ((ϕ_{S2} minus (ϕ_{S6}) and then fine tuning the timings and offsets to adjust for queues at the interface-link.

The lower part of Figure 21 illustrates the case when left-turn phase S5 at the adjacent signal leads and left-turn phase S1 lags. In this case, perfect progression for traffic traversing the interface link can be obtained by setting phase ϕ_{d5} equal to Φ_S plus the difference between the lengths of phases for movement S2 and S1 (ϕ_{S2} minus ϕ_{S5}).

The reader should note that the last two cases discussed above require a larger cycle length than the first case. This increase depends on the magnitude of the overlap phase at the signal. The other two cases are:

1. Signal phases for movements S1 and S5 lead, with phase S5 larger than phase S1. In this case, two-way progression can be achieved when ϕ_{d5} is equal to Φ_S minus the overlap (ϕ_{S5} minus ϕ_{S1}).
2. Signal phase ϕ_{S1} leads and ϕ_{S5} lags. In this case, $\phi_{d5} = \Phi_S - \phi_{S1}$.

In the above, we discussed the relationships between the length of interior left-turn phase at the interchange and the sum of travel times at the interface link for various phase sequences for the arterial at the adjacent signal. Similar relationships can be derived for three-phase diamond operations. Now we are ready to propose two strategies.

Proposed Strategies

Here we assume that the analyst has already determined that TTI four-phase is the best strategy for the diamond interchange. Recall that this decision is made based on the (stop-bar to stop-bar) distance between the two intersections of the interchange. The next step is to select the best cycle-length range, which includes the cycle length that provides the maximum throughput capacity for the observed pattern of demand at the interchange.

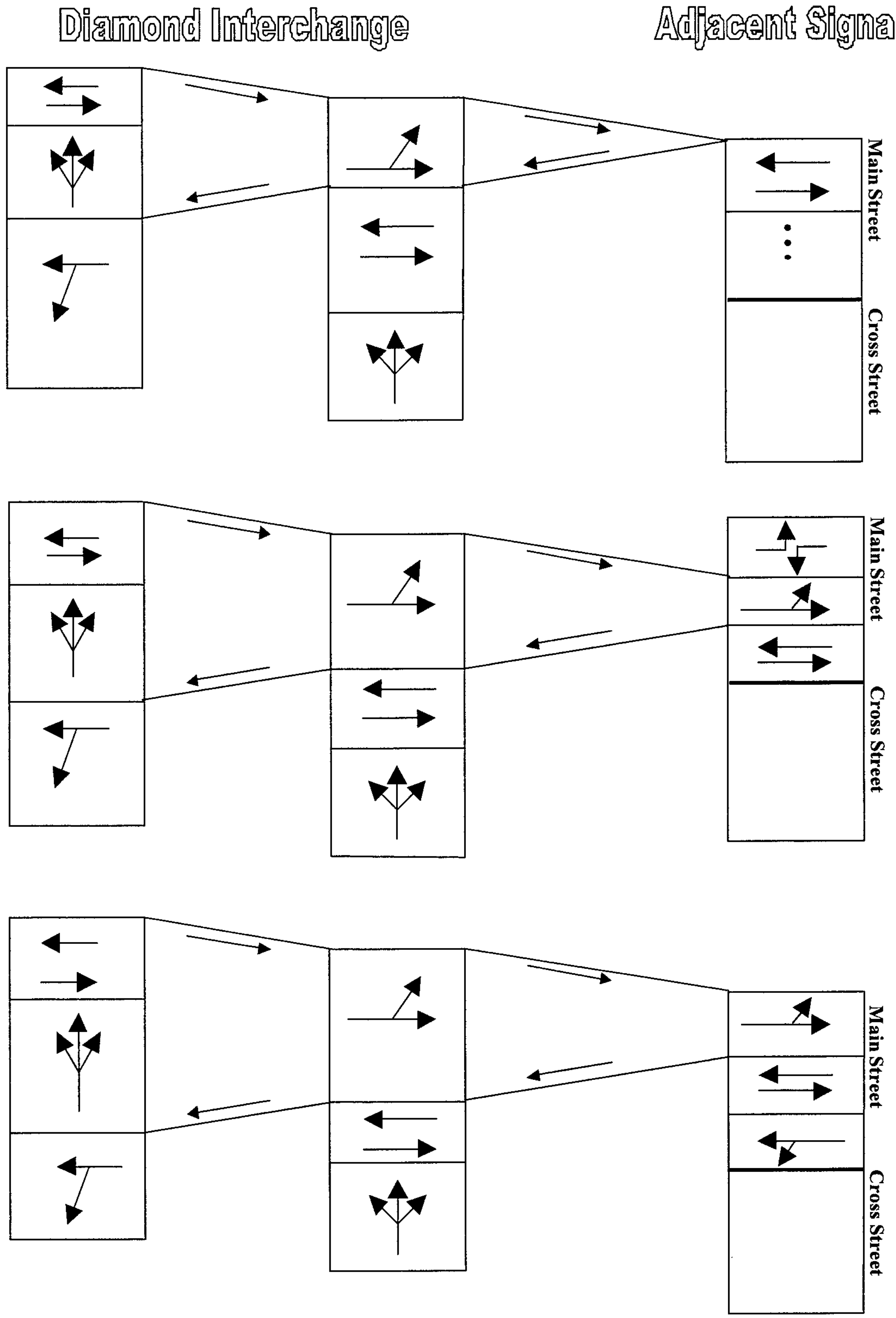


Figure 21. Some Cases in Which Two-way Progression with Adjacent Signal is Possible.

One can determine the best cycle length by using the LP procedure described in the previous chapter. The advantage of using the full procedures is that it will also point to the capacity bottleneck. As an alternate, the analyst can use one of the six plots provided in that chapter. Using the plots requires the following steps:

1. Determine the pattern of demand (e.g. heavy traffic on left side and light traffic on the right side) and select the appropriate plot,
2. Determine the cycle length that provides maximum throughput capacity. Based on this cycle length select a range for cycle length,
3. Add the exterior demands to determine if it is undersaturated or oversaturated case. If it is an oversaturated case, use the procedures described in the next section.

Strategy I

This is the simplest strategy and requires the following steps:

1. Select a cycle length.
2. Determine travel times for the interchange and the interface-link. Appendix B provides an example and travel time tables for use by analysts.
3. Use PASSER III to determine timings for the interchange.
4. Use PASSER IV to coordinate right intersection of the interchange with adjacent signal(s) on the right side. The same procedure can be repeated if there are signals on the left side of the interchange.
5. Repeat the above steps for all cycle lengths in the selected range.
6. Select the timing plan that provides best two-way progression.
7. If this analysis shows that two-way progression is not possible, use the best cycle length for the interchange, and provide one-way progression in the heavy flow direction. The reader should note that one-way progression with the adjacent signal can always be achieved.

The advantage of using PASSER IV is that it can be asked to use a given set of splits and phase sequence(s) for some intersections while asked to calculate these parameters for the others. In this case, the user will provide phase sequence and splits for the right intersection of the diamond, link speeds (speed for a link can be calculated using the corresponding travel time and travel distance), and volumes for the adjacent signal(s).

Strategy II

1. Select a cycle length.
2. Calculate phase times for the adjacent signal using Webster's formula.
3. Identify the set of possible phasing sequences for the adjacent signal.
4. Use the tables provided in Appendix B to obtain travel times for the interchange and the interface-link.
5. Use relationships described earlier to find the ideal length of phase ϕ_{d5} for each phase sequence from the above set.
6. Use the following relationships to determine actual length of phase ϕ_{d5} for the selected cycle length and travel times:

$$\phi_1 = \frac{1}{y_2 + y_4 + y_6 + y_8} \times ((C - 2l) \times (y_6 + y_8) - (\Phi - 2l) \times (y_2 + y_4))$$

$$\phi_5 = \frac{1}{y_2 + y_4 + y_6 + y_8} \times ((C - 2l) \times (y_2 + y_4) - (\Phi - 2l) \times (y_6 + y_8))$$

7. Compare the length of phase calculated in Step 7 to each value obtained in Step 6. Select the ideal phase length from Step 6 that is closest to the value calculated in Step 7. Also, select the corresponding phasing sequence at the adjacent signal.
8. Repeat Steps 2 through 7 for each cycle length in the set. Select the best cycle length and adjacent-signal phase sequence combination and calculate length for external phases of the diamond using equations provided in the last chapter.
9. If no satisfactory combination is found, select optimum cycle length for the interchange and provide one-way progression for the travel direction with the heaviest traffic flow.

AN ADVANCED TIMING APPROACH

In the previous section, we provided simple strategies and guidelines for coordinating a diamond interchange with an adjacent traffic signal. We discussed the use of these strategies for one adjacent signal. The methods presented can be applied to cases where an adjacent signal is present on both sides of the diamond interchange. The strategies described previously will work well as long as blocking does not occur on the interface links. This assumption may not be true for heavy traffic conditions or for congested situations. In this section, we develop an iterative procedure that can be applied to all types of traffic conditions. In fact, this procedure can also identify whether demand for a diamond-interchange and adjacent signal system is more than capacity or not. Before proceeding, however, it would be appropriate to characterize various congested situations.

In systems with closely spaced signals, traffic flow problems can occur due to the two reasons described below:

1. Demand is above the capacity of the system.
2. Queues and blocking at an interior (or exterior) link are causing a loss in capacity. This may happen either because of non-optimal signal timings and/or lack of coordination between the intersections.

In the first case, the only option is to implement demand reduction techniques or to increase the system capacity through reconstruction. In the second case, full system capacity can be realized by selecting optimal signal timings and by coordinating the signals (including a diamond interchange) in the system. In this section, we develop procedures for dealing with both cases described above. This procedure is based on a philosophy of dealing with all components of a problematic set of signals as one system instead of treating them as isolated components.

Figure 22 illustrates two configurations of a diamond interchange signal system. In this figure, we use rectangular boxes to identify where traffic flow problems might be originating.

Drawing a rectangular box around the system of concern allows us to define two types of links: external (identified using arrows) and internal (identified using bold lines). The top part of the figure shows a problematic system that includes a diamond interchange and one adjacent signal on the right side. The bottom part of this figure shows the case where the link joining the diamond interchange and the adjacent signal on the left is also experiencing traffic flow problems. In this case, this external link must also be included in the system, which changes its designation to an internal link.

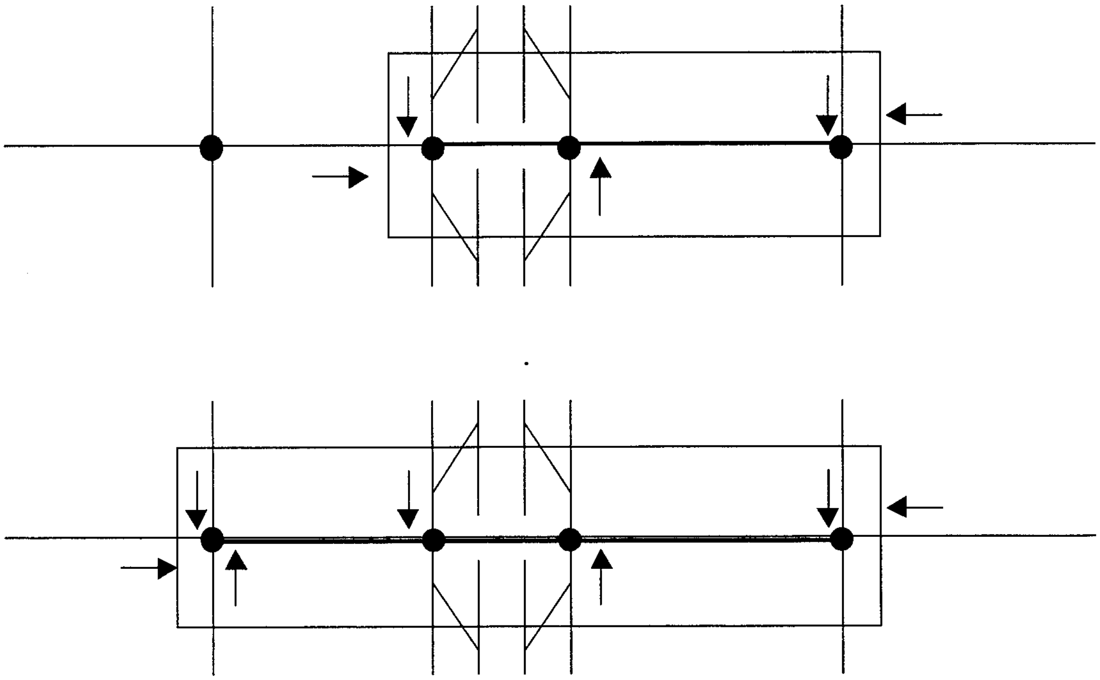


Figure 22. Problematic Diamond Interchange-Signal System.

Now, recall the survey responses about the priorities and objectives of operation we presented in Chapter 3. As reported, the engineers/technicians identified "preventing queues on the frontage roads from interfering with the ramps" as the highest priority objective. Preventing queues from an adjacent signalized intersection (diamond interchange) from blocking the diamond interchange (adjacent signal), was ranked by the respondents as a low priority objective. However, many times, long queues at frontage roads (external links) are a result of insufficient capacity at the interior link (e.g., the interface link). Thus, we submit that resolving these problems is essential in preventing the formation of long queues on the frontage roads and other exterior approaches in the selected system. In other words, the interior system links must have sufficient capacity (green times) to efficiently handle traffic arriving from the exterior approaches. Providing sufficient green time for interior movements may not be sufficient for short links if the bulk of the traffic arrives when the signal is red. Thus, good progression is another essential ingredient to an efficient operation. Also, any capacity problems at the exterior approaches should be resolved. Last but not least, the selected system cycle length should be as short as possible for keeping the maximum cycle-by-cycle queues short. The signal timing strategy developed in this project is based on these principles. We present this strategy in the following subsection.

A Systems-Based Strategy for Timing Diamond Interchange Environments

This section describes a system-based strategy for timing a system having one diamond interchange and up to two adjacent signals, one on each side of the interchange. The philosophy used by this strategy is generic in nature and can be extended to include any number of adjacent signals. The strategy presented here is iterative in nature and consists of the following two steps:

1. Determine optimal green splits.
2. Coordinate the interchange with adjacent signals.

The first step, green split calculations, of the iterative procedure seeks to simultaneously achieve the following two objectives:

1. Maximize the throughput capacity of the system while preventing blocking on interior links.
2. Select splits for all exterior movements such that any queues on exterior approaches grow at the same rate.

In order to achieve the first objective, the green split calculation process keeps the volume-to-capacity ratios for the interior movements below 0.95. We chose a value of 0.95 to maintain undersaturated flow conditions at all interior links. The second step, coordination process, assesses if good coordination can be achieved using the splits calculated in the first step. If good progression cannot be achieved, the procedure adjusts the cycle length and green splits until it achieves the desired results. The coordination step uses guidelines presented in the previous section.

Green Split Calculations

Here, we assume that the demand (volume) at each exterior movement is less than the saturation flow rate for each movement. The following steps outline the green split calculation for the complete system:

1. Select a cycle length range.
2. Start with the smallest cycle length from the above range.
3. For each external movement, determine the green split using the following relationship:

$$g_i = C * \frac{v_i}{s_i}$$

Where:

g_i is effective green for movement i,

C is the cycle length,

s_i is saturation flow rate for movement *i*, and
v_i is volume for movement *i*.

4. Allocate the remaining green time in the cycle to the interior movements.
5. For each interior movement, estimate minimum green time needed to clear the incoming traffic.
6. If any of the interior green time is less than its corresponding minimum green time, decrease the green times for all exterior movements by a specified factor and go to step 4. This will ensure that any resulting queues at the exterior movements will be balanced. The new exterior green times will be equal to:

$$g_i = (C - \delta) * \frac{v_i}{s_i}$$

where: δ is reduction factor.

7. For each interior movement, estimate the maximum queue and compare it to the available storage. If sufficient storage space is not available, reallocate some external green to internal movements as per Step 6, and go to Step 4.
8. Uncoordinated timing plan is found.

Step 4 of the above procedure assumes that the allocation of cycle time to phases of a Signal is independent of other signals in the system. This is not true for TTI four-phase strategy. For TTI four-phase, the green time for interior left-turn movement at the right intersection of the diamond is related to the exterior phases at the left intersection, and vice versa. Thus, increasing the length of an interior left-turn phase at one signal also requires increasing the lengths of exterior phases at the other signal of the interchange. Because of this relationship, Step 6 described above must be modified. For example, if our system has a diamond interchange and adjacent signals on the right side only, we will need the following modifications:

a. If g_{d5} is less than its corresponding minimum green time and any one of the other interior green time is less than their corresponding minimum green time, there is no four-phase timing plan. Stop.
b. If only g_{d5} is less than its corresponding minimum green time, increase this green phase as well as exterior green times at the other signal of the diamond interchange.
c. If any of the interior green time, except g_{d5}, is less than its corresponding minimum green time, decrease exterior green.

As mentioned earlier, the coordination phase for this strategy consists of the same options we presented earlier for the simple coordination strategy. Thus, the only difference between the two procedures is in the calculation of green splits. When a system has more than one adjacent signal on the arterial, the arterial can be broken into sub-components as shown in Figure 23.

Figure 23 shows an arterial system with multiple signals on one side of the interchange. In such systems, the following steps can be used for providing arterial coordination:

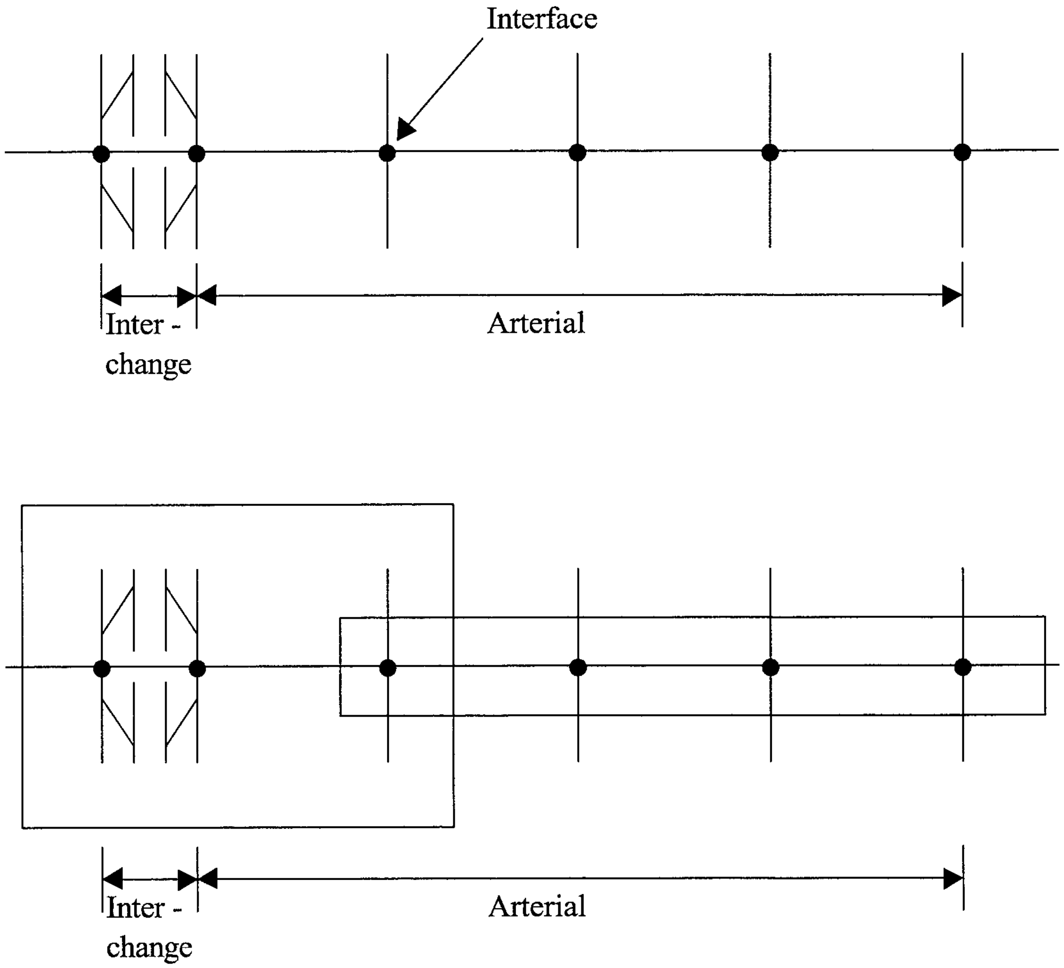


Figure 23. An Approach for Coordinating Large Systems.

1. Define the signal immediately next to the interchange (or the second next signal if the adjacent signal mostly carries through traffic) as the interface between the interchange and the remaining signals on the arterial.
2. Coordinate the diamond interchange with the interface signal using procedures described in this section.
3. Retain the timings obtained in Step 2 for the interface signal and coordinate it with the remaining signal on the arterial using PASSER II or PASSER IV.

Enhancements

The advantage of the system-based approach to timing diamond interchanges and adjacent signals presented here is that it applies to all types of traffic conditions. In case of congestion, this approach shifts the location of queues from interior approaches to exterior approaches. The resulting queues at the exterior approaches will keep growing as long as peak demand exceeds capacity of the system. Because of safety concerns for exit-ramp traffic, an engineer may wish to provide more green time for a frontage road phase at the expense of the arterial phase. The above approach can be easily modified to achieve this result. For undersaturated systems, the cycle-by-cycle queues will be stable. In such situations, additional adjustments to green splits to shift some slack time back to external approaches will result in a more robust signal-timing plan. A robust timing plan will have the ability to handle additional demand (increased demand or cycle-by-cycle variations due to randomness). Mathematically, we define robustness of a signal-timing plan as:

$$Robustness = \max\left(\frac{1}{\text{max exterior v/c ratio}}, \frac{0.95}{\text{max interior v /c ratio}}\right) - 1$$

If there are multiple timing plans for an undersaturated system, the solutions with the highest robustness value will be the best. For instance a robustness value of 0.2 for a signal-timing plan means that this timing plan can accommodate 20 percent more traffic than the current level of demand.

VERIFICATION AND TESTING

Testing and application of the procedures developed in this project, especially the capacity analysis technique and the system-based timing and coordination approaches, had to be done in a limited amount of time. This required the researcher to use an automated process for conducting repetitive calculations. However, since software development was outside the scope of this project, we decided to use a computer spreadsheet to facilitate our analysis.

6. APPLICATIONS TO REAL PROBLEMS

One of the project tasks required using real data to verify the usefulness of guidelines and procedures developed in this project. In this chapter, we present the application of research results to two sites in Texas. The first site is located in Corpus Christi and the other in Weslaco.

INTERCHANGE AT SH 358 AND AYERS STREET

This site is located at the intersection of SH 358 (South Padre Island Drive) and Ayers Street in Corpus Christi, Texas. This diamond interchange has an internal spacing of 333 feet. Furthermore, there is an adjacent signal (Line P) 387 feet south of the interchange. Figure 24 presents a layout of this system. This was one of three sites that researchers observed during a visit to Corpus Christ in December 1999. Although this site was not as congested as the other two, TxDOT staff and researchers agreed to use it in this research project. The reason for this decision was that TxDOT operates the system (the interchange and the adjacent signal), and the logistics of implementing improved signal timings would be straightforward.

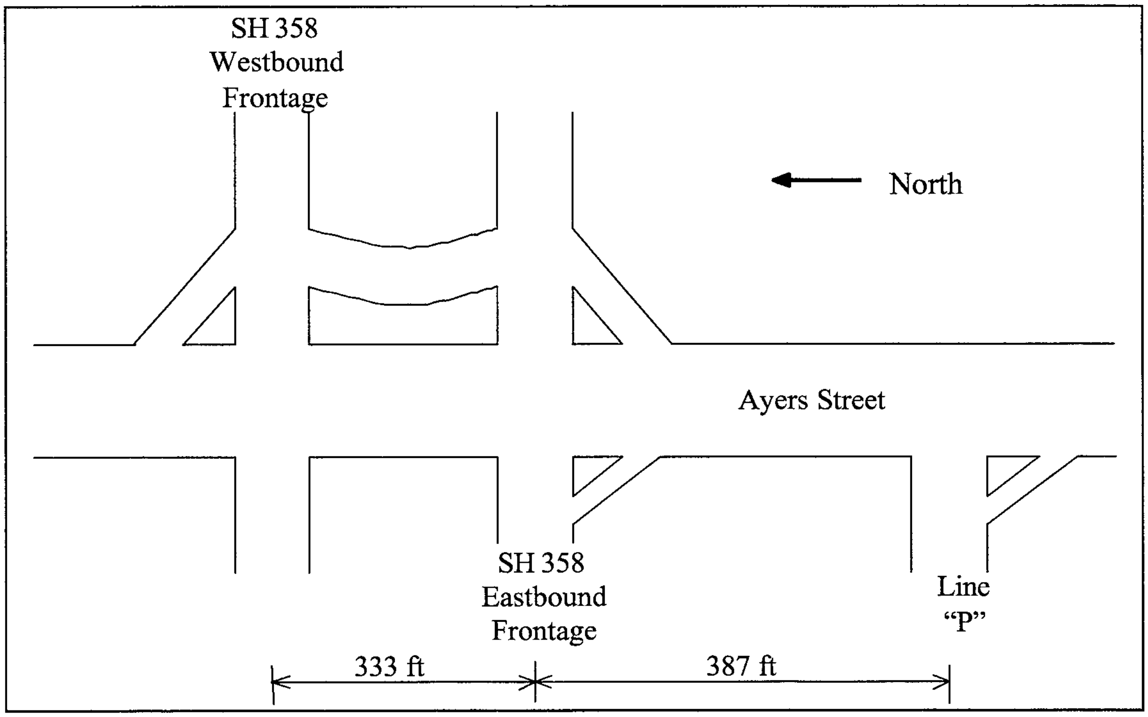


Figure 24. SH 358 Interchange System in Corpus Christi.

This site experiences heavy northbound traffic during morning peak period. The peak period, however, is short (less than an hour). During this period, there is light traffic in the eastbound direction. Also, there is significant interior left-turn traffic on the north intersection of the diamond interchange.

Data Collection

This site, like most other sites maintained by the Corpus Christi District, has video cameras installed on all major approaches. At the researchers' request, TxDOT staff videotaped the operation of this facility. The researchers used the videotape recorded on May 9, 2000 to obtain the volume counts. Initially, we counted traffic volumes for five-minute intervals. For further use and analysis, we added three contiguous five-minute intervals to obtain a set of moving 15-minute counts. For example, the first 15-minute count consisted of the first three five-minute counts; the second 15-minute count was the sum of second, third, and fourth 5-minute count, and so on. Finally, we selected the most critical 15-minute counts and converted them to hourly flow rates. Figure 25 shows the hourly flow rates used in the analysis presented here.

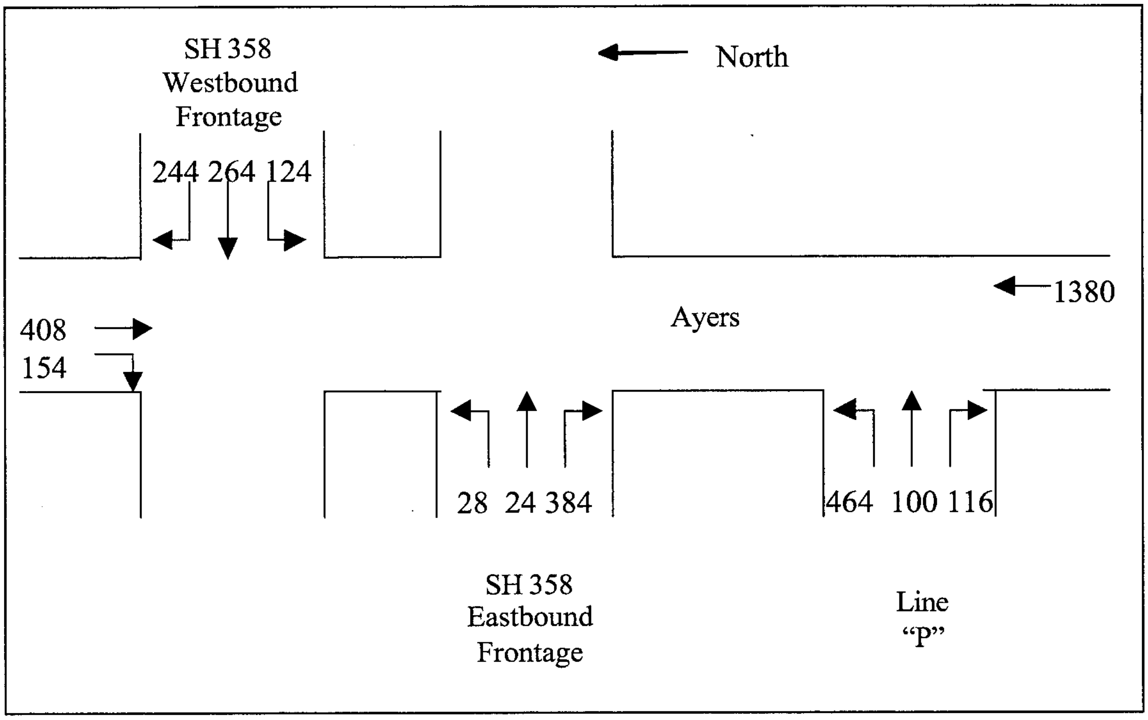


Figure 25. Hourly Flow Rates for the Ayers System.

Throughput Capacity Analysis

First, we analyzed the throughput capacity using the LP-based procedure described earlier. The main purpose of this analysis was to determine a range of cycle lengths. Since the internal distance for the interchange is 333 feet, we selected TTI four-phase operation. However, for comparison purposes, we decided to include the two three-phase strategies in this analysis. Figure 26 illustrates the results.

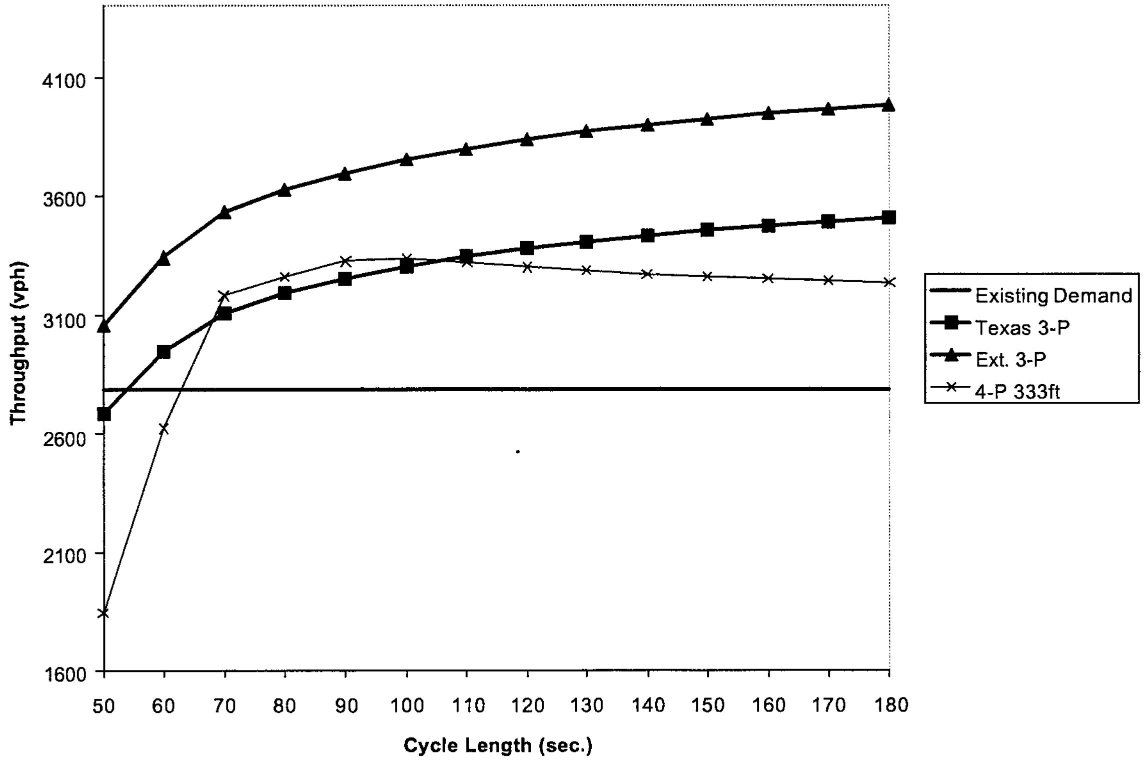


Figure 26. Capacity Analysis of Ayers System.

As can be seen from Figure 26, the capacity of the TTI four-phase operation is lower than the capacity of extended three-phase. However, for cycle lengths between 70 and 100, its capacity is more than that of the Texas three-phase operation. Also, a cycle length of 100 seconds provides the maximum capacity (3339 vph) for the TTI four-phase operation. From the figure, the reader can also see that the system demand of 2788 is well below this capacity.

Timing Plan Development

We used the system-based procedure (heuristic) described in the previous chapter for developing the timing plan (green split calculations and coordination) for this system. Although our capacity analysis indicated that the optimal cycle length range is between 70 and 100 seconds, we used a range of 50 to 120 seconds. The purpose of this selection was to verify the results of the procedure for developing the timing plan.

The heuristic confirmed that a 50-second cycle length does not provide sufficient internal green times. The heuristic showed that coordination is not possible for cycle lengths of less than 70 seconds. The heuristic also indicated that for cycle lengths longer than 100 seconds, coordination results in reduced throughput capacity. Cycle lengths of 70, 75, 80, 85, 90, 95, and 100 provided good progression. The 85-second cycle length had the maximum robustness of 0.167. Figure 27 shows the recommended timing plan.

Morning: Cycle Length = 85 seconds

Diamond Interchange

Offset Reference Point: Beginning of Phase 2

Offset = 0 seconds

4-Phase Diamond: Internal Offset = 11 seconds

Phase	1	2	3	4	5	6	7	8
Street Direction	Ayers NB LT	Ayers SB		F.R. WB	Ayers SB LT	Ayers NB		F.R. EB
Phase Time	46	20		19	17	40		28

Ayers at Line "P"

Offset Reference Point: Beginning of Phase 2

Offset = 20 seconds

Main Street (FM 88): Lag-Lag

Phase	1	2	3	4	5	6	7	8
Street		Ayers			Ayers	Ayers		Line "P"
Direction		SB			SB LT	NB		EB
Phase Time		47			5	47		33

Figure 27. Recommended Timings for Corpus Christi System.

Verification Using CORSIM

Finally, we used CORSIM to verify the timing plan recommended by our heuristic. To verify the stability of the proposed timings, we ran the simulation for one hour. Visual observation of animation of existing and proposed timings, illustrated in Figures 28 and 29, shows that the recommended timing plan is extremely stable in that there is no spillback at any intersection in the system. Furthermore, the control delay for all the interior movements is less than 10 seconds per vehicle and for all exterior movements the control delay is less than 32 seconds per vehicle. Also, no vehicle stops at a signal approach for more than one cycle.

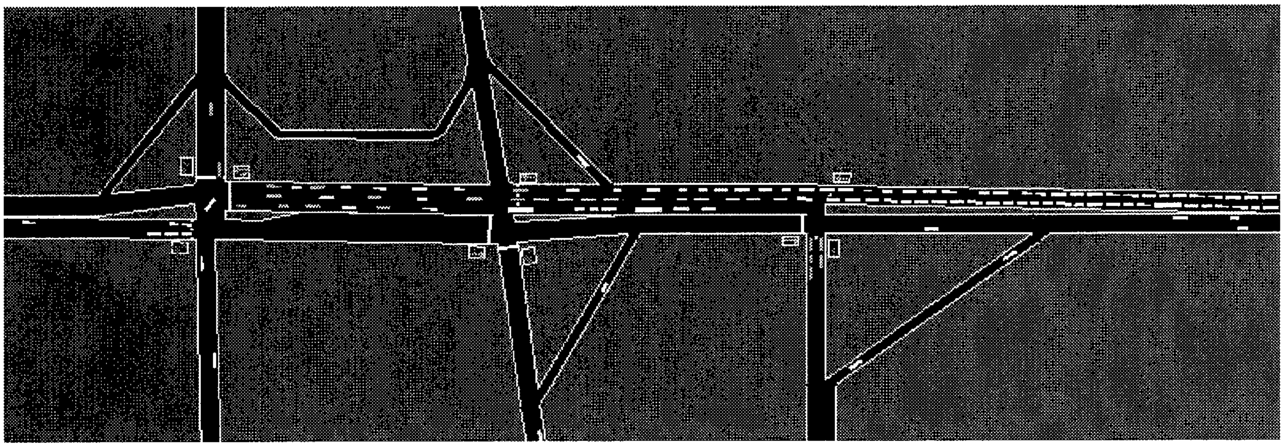


Figure 28. Existing Timing Plan for Ayers System.

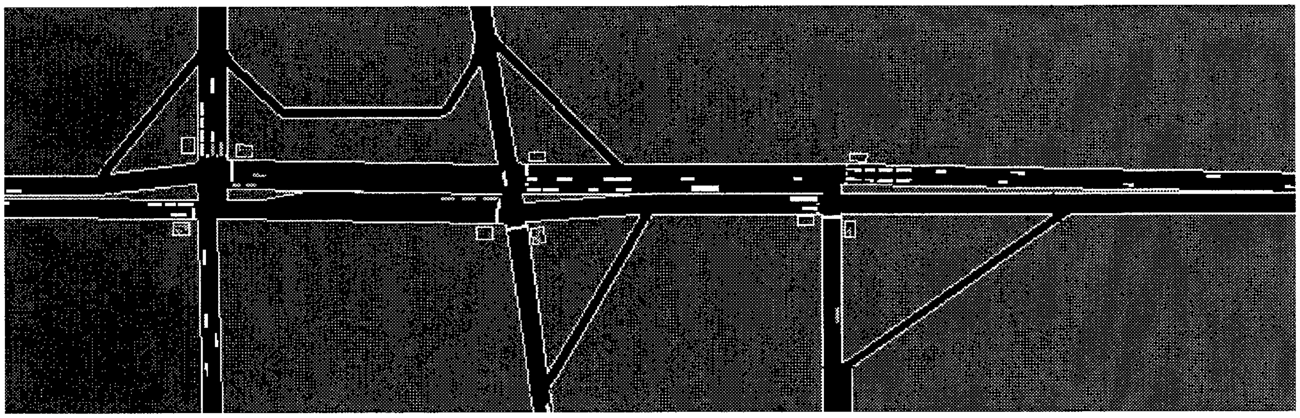


Figure 29. Optimized Timing Plan for Ayers System.

INTERCHANGE AT U.S. 83 AND FM 88

The second study consisted of analysis and timing of a diamond interchange and adjacent signal (Pike Boulevard) located on FM 88 in Weslaco, Texas. At this site, the width of the diamond interchange is 256 feet and the adjacent signal at Pike Boulevard is located about 1000 feet south of the interchange. Furthermore, the interchange has full left-turn lanes in each direction. The area between the interchange and the adjacent signal is densely developed with several driveways providing access to a large shopping area, which includes an HEB, a gas station, and several restaurants. During peak periods, weaving caused by vehicles turning to and from the driveways, causes traffic flow problems at the link. This results in reduced speeds and a significant reduction in the capacity of the system. Based on a recent study conducted for the district by a consultant, a construction project is underway to signalize the driveway providing access to the H.E.B shopping area. Figure 30 shows a sketch of this system.

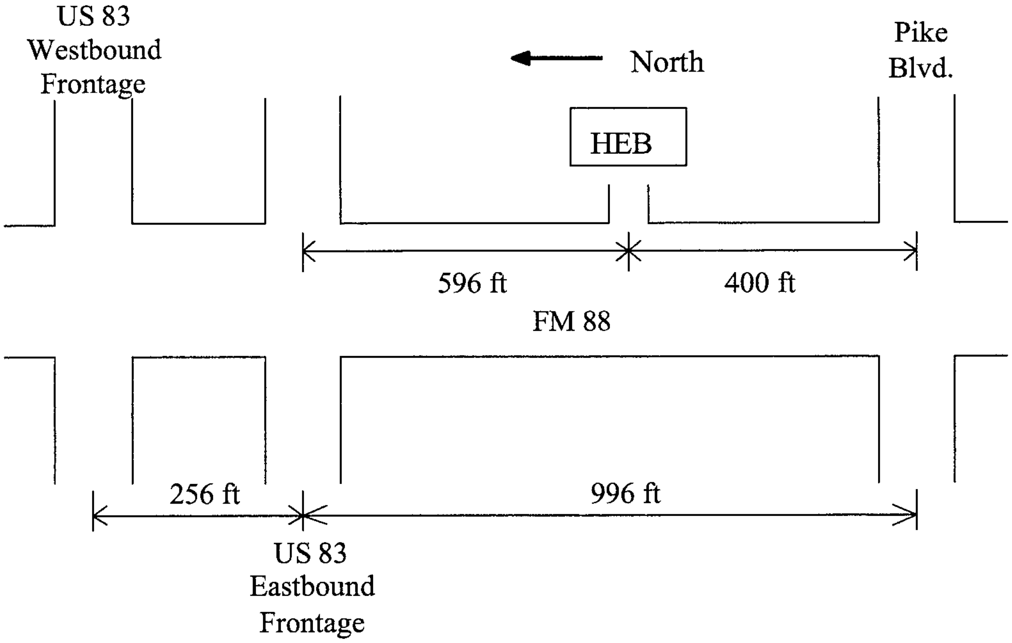


Figure 30. The Weslaco System.

Before the implementation of timings developed in this study, the interchange and the adjacent signal were being operated in actuated and isolated modes. Furthermore, the maximum actuated cycle length (sum of max times for the critical phases) for the interchange was 120 seconds and that for the intersection was 118 seconds. The researchers believed that these were two potential causes for traffic flow problems within the system, especially the interface link.

Data Collection

For this study, we used data collected at two different times. The first set of data was collected for the district by a consultant in May 1996. This data collection was part of a study to develop signal warrants for the driveway providing access to the HEB shopping area. The second set of data was collected at the researchers' request by the district staff in July of 2000. It is costly and time consuming to collect origin destination data for all driveways. Therefore, we only used the data collected by the consultant for the main entrance of HEB. We used these (to-and-from) volumes to determine the volumes arriving at the downstream traffic signals of the interface link.

Since hourly flow rate is required to perform the throughput analysis, we took the data for the most critical five-minute volumes and converted these volumes to hourly flow rates. From these data, we created two cases: noon peak and evening peak. Figure 31 and 32 show these data. For analysis purposes, we assumed a free-flow speed of 45 mph for both directions of flow. We also assumed 2 percent heavy vehicles on each approach.

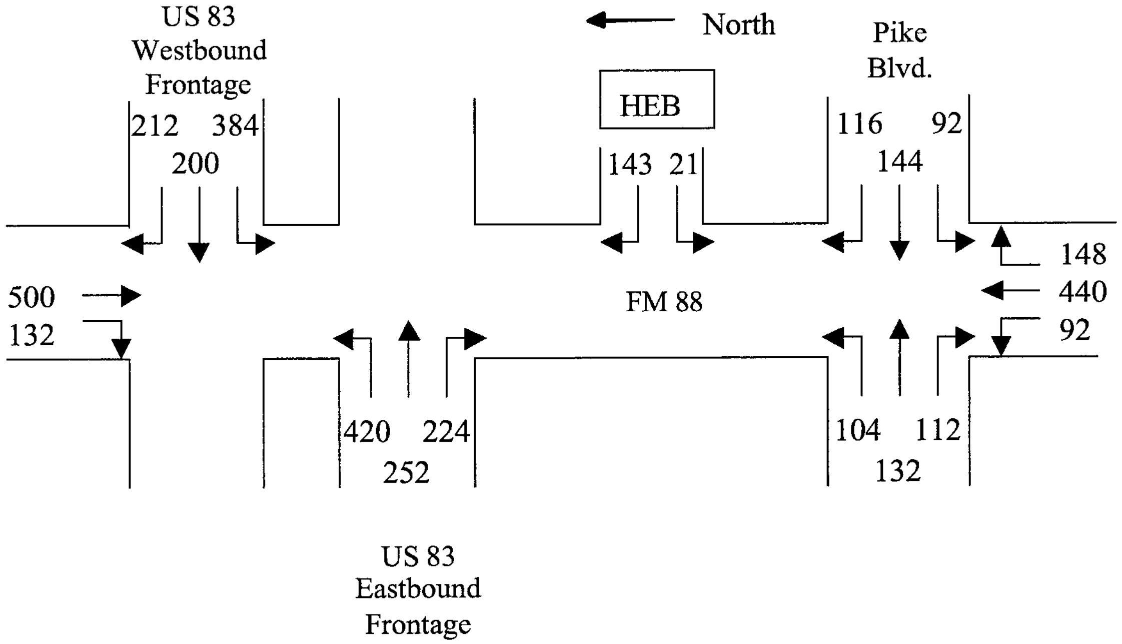


Figure 31. Noon-Peak Data for the Weslaco System.

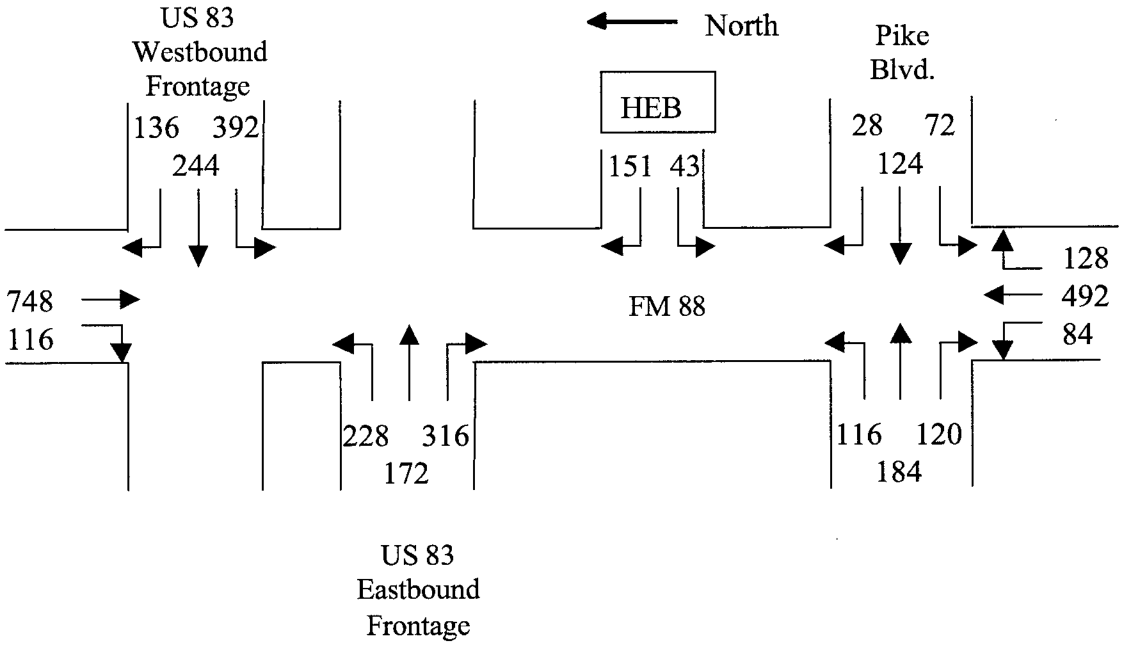


Figure 32. Evening-Peak Data for the Weslaco System.

Throughput Analysis

Figures 33 and 34 illustrate the results of capacity analysis of the system for the noon and the evening periods. As can be seen from these figures, the demand is well below the ideal capacity of the system. For the noon period, even a cycle length of 50 seconds is sufficient to handle the existing traffic demand; however, we need a minimum cycle length of 70 seconds to satisfy pedestrian requirements. A 90-second cycle length provides maximum capacity for this period. For the evening-peak, a cycle length of 70 seconds (which also satisfies pedestrian minimums) is sufficient, but the maximum capacity occurs at the 140-second cycle length.

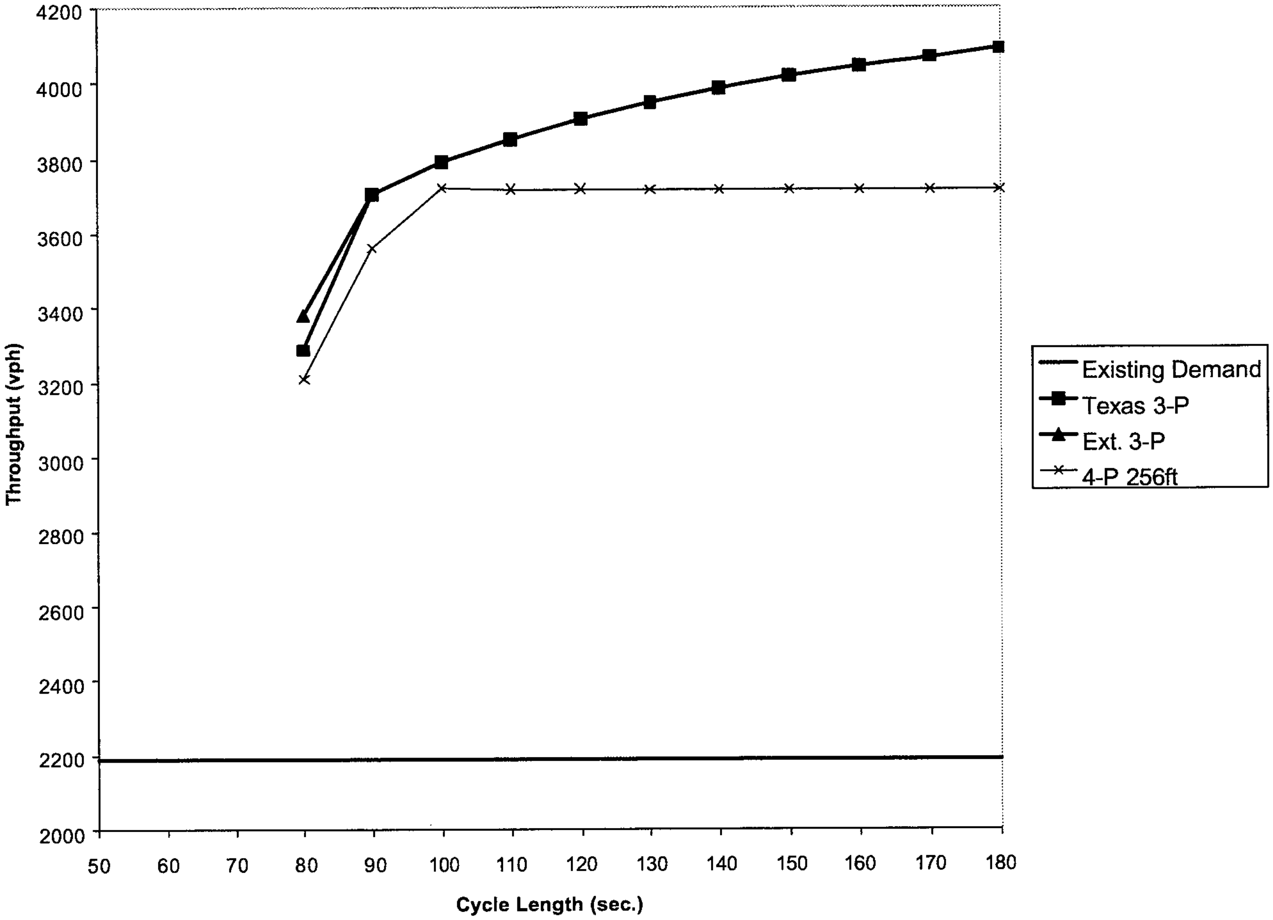


Figure 33. FM 88 Throughput Capacity Analysis for Noon Peak Period.

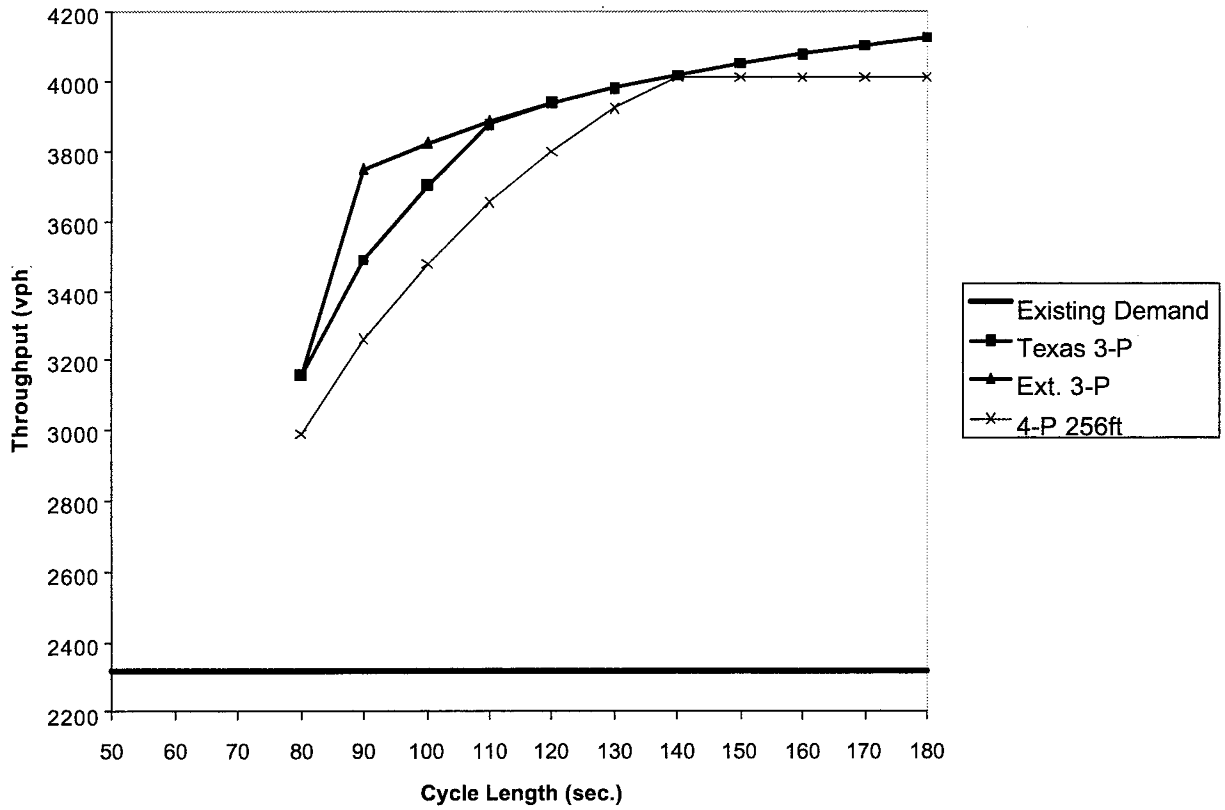


Figure 34. FM 88 Throughput Capacity Analysis for Evening Peak Period.

Timing Plan Development Using Heuristic Method

The throughput analysis described above shows that the system is undersaturated during both time periods. Also, for both cases, a cycle length in the 70- to 110-second range is sufficient to satisfy minimum times based on pedestrian requirements and to provide flexibility in achieving coordination. Thus, we evaluated cycle lengths in the above range with 5-second increments. Also, we chose a target interior volumes-to-capacity ratio of 0.95. Furthermore, our analysis resulted in travel times of 12 and 20 seconds for the interchange and the interface link, respectively. We selected an internal offset of 12 seconds (travel time minus 2 seconds) for the diamond interchange. For the interface link, we selected an offset of 16 seconds (travel time minus 4 seconds) to provide some queue clearance time for side street traffic. Also, since the interior diamond link is 256 feet long, we used TTI four-phase strategy for the diamond interchange.

Noon-Peak Analysis

The analysis showed that no coordinated timing plan exists for cycle lengths of less than 85 seconds. Furthermore, the heuristic procedure found a timing plan for each cycle length from 85 seconds to 110 seconds. The heuristic procedure found that the lag-lag phasing is best for the main street at the adjacent signal. Since this is an undersaturated case, all cycle lengths result in the same throughput. Therefore, the timing plan with the maximum robustness value will be the best. Further analysis indicated that the timing plan with a 90-seconds cycle length produced the maximum robustness value of 55 percent. This means that the timing plan generated by the heuristic method can handle up to 55 percent more traffic than the current demand. Figure 35 shows this timing plan.

Evening-Peak Case

In this case, our heuristic method found timing plans for all cycle lengths in the range of 80 to 110 seconds. The reader will note that this range is almost the same as that for the previous case. This similarity, however, is not by chance. Recall that in a coordinated system of signals, travel times on internal links have large influences on the selection of system cycle length. Thus, the similarity resulted from the use of same travel times for both time periods.

We also calculated the robustness values for each of timing plan (cycle length). Among all timing plans, the one with an 85-seconds cycle length had the largest robustness of 38 percent and thus, was chosen for further analysis. Figure 36 shows this timing plan.

Comparison with Other Timing Plans

Previously, we described several ways to coordinate a diamond interchange with adjacent traffic signals. For the FM 88 system, we compared the results obtained by using the heuristic method with two additional plans: one-way progression and two-way progression using PASSER IV. For these two cases, we used the best cycle length generated by the heuristic method. This resulted in the following four simulation cases:

Cycle Length = 90 seconds

FM 88 at US 83 Frontage Road

Offset = 0 seconds; Offset Reference Point: Beginning of Phase 2
4-Phase Diamond: Internal Offset = 10 seconds

Phase	1	2	3	4	5	6	7	8
Street Direction	FM 88 NB LT	FM 88 SB		F.R. WB	FM 88 SB LT	FM 88 NB		F.R. EB
Phase Time	38	24		28	32	27		31

FM 88 at Pike Road

Offset = 26 seconds; Offset Reference Point: Beginning of Phase 2
Main Street (FM 88): Lag-Lag; Cross Street (Pike): Lag-Lag

Phase	1	2	3	4	5	6	7	8
Street Direction	FM 88 NB LT	FM 88 SB	Pike EB LT	Pike WB	FM 88 SB LT	FM 88 NB	Pike WB LT	Pike EB
Phase Time	12	38	13	27	20	30	13	27

Figure 35. Noon-Peak Timing Plan for the Weslaco System.

Cycle Length = 85 seconds

FM 88 at US 83 Frontage Road

Offset 0 Seconds; Offset Reference Point: Beginning of Phase 2

4-Phase Diamond: Internal Offset = 10 seconds

Phase	1	2	3	4	5	6	7	8
Street Direction	FM 88 NB LT	FM 88 SB		F.R. WB	FM 88 SB LT	FM 88 NB		F.R. EB
Phase Time	32	25		28	33	28		24

FM 88 at Pike Road

Offset 26 seconds; Offset Reference Point: Beginning of Phase 2

Offset = 26 seconds

Main Street (FM 88): Lag-Lag; Cross Street (Pike): Lag-Lag

Phase	1	2	3	4	5	6	7	8
Street Direction	FM 88 NB LT	FM 88 SB	Pike EB LT	Pike WB	FM 88 SB LT	FM 88 NB	Pike WB LT	Pike EB
Phase Time	11	35	16	23	16	30	11	28

Figure 36. Evening-Peak Timing Plan for the Weslaco System.

- Heuristic Timing Plan (TP) is developed using our heuristic.
- One-way (TP) is generated using Webster's formula to calculate splits for the adjacent signal, and by providing one-way progression from the interchange to the signal.
- PASSER-TP is generated by using PASSER IV.
- Current-TP is the existing timing plan.

Timing Plans for the Noon-Peak Period

Simulation of the above cases showed that all three coordination plans performed better than the existing case where the district provided no coordination between the interchange and the adjacent signal. When comparing the three methods of coordination, we found the following:

- Because this is an undersaturated system, throughput is the same for all three.
- There is no significant difference in control delay for the exterior approaches.
- There is no significant difference in control delay for the interior links of the diamond interchange. This is because all coordination methods used TTI four-phase strategy.
- Heuristic TP produced less control delay for the interface link. Researchers expected this since the heuristic method ensures volume-to-capacity ratios of 0.95 or less on interior links.

Timing Plans for the Evening-Peak Period

As for the Noon-Peak, we found that coordinating the diamond with the adjacent signal improved signal timing. Additional results were also similar to the Noon-Peak case.

Analysis of Robustness

As described in the previous subsection, our heuristic procedure results in better timing plans than the other (simpler) coordination method suggested in this report. In this section, we present the results of additional sensitivity analysis of the two timing plans (Noon- and Evening-Peak) produced by the heuristic method.

Noon-Peak Timing Plan

As stated earlier, the robustness value of the proposed timing plan is 0.55. This means that this timing should work well even when the existing demand increases by up to 55 percent. In order to test the performance of this timing plan, we performed several simulation runs by successively increasing the traffic demand. Table 23 provides throughput values for the cases when we increased the current demand by 20, 40, 50, 55, and 60 (Case-20, Case-40, etc.) percent. From this table, one can see that the throughput increases as the demand increases. This will be true as long as the demand is less than the capacity of the system. Further, the results show that the timing plan performs very well for Case-20 where the maximum increase in control delay on each link is less than 4 seconds. For Case-40 and Case-50, there is no spill back, and the control delay of the exterior links increase as compared to lower demand.

Table 23. Performance of Noon-Peak Plan.

Case	Throughput (vph)
Base Case	2326
Case-20	2807
Case-40	3251
Case-50	3481
Case-55	3598
Case-60	3719

The simulation shows that the proposed timing plan is barely adequate for Case-55. Under this scenario, southbound traffic sometimes needs to wait for two-signal cycles to get through the adjacent signal. Also, the driveway providing access to HEB is often blocked by the southbound traffic. The simulation further shows that the timing plan is inadequate for Case-60. Under this scenario, the south intersection of the diamond interchange was blocked a few times during simulation. Also, simulation shows a queue buildup on the interface link. Simulation further shows that the delay to vehicles increases significantly.

Evening-Peak Timing Plan

The robustness value of this timing plan is 0.38. Thus, this plan should be able to handle an increase in demand of up to 38 percent of the current demand. In order to verify this, we simulated three cases of increased demand (20 percent, 40 percent, and 50 percent). Table 24 presents the throughputs obtained for each of these cases from CORSIM.

Table 24. Performance of Evening-Peak Plan.

Case	Throughput (vph)
Base Case	2501
Case-20	2992
Case-40	3509
Case-50	3599

Note that the throughputs for Case-20 and Case-40 are about 120 percent and 140 percent, respectively, of that for the base case. However, the throughput for Case-50 is only 143 percent of the base case throughputs. It is an indication that the timing plan is not adequate for Case-50.

For Case-20, there is a small increase in control delays at the exterior and interior links, while no spillback occurs. For Case-40, the increase in control delays for the exterior links is still acceptable. However, the control delays of the interior link from the diamond interchange to the adjacent signal increase significantly. The entrance to the HEB shopping area is often blocked by the southbound traffic. Overall, heuristic TP still performs very well in clearing the interior traffic. For Case-50, simulations show that demand is more than capacity. In this case, queues on the southbound links grow very fast, resulting in blocking at both intersections of the interchange.

Implementation of Proposed Timings

On August 15, 2000, the researchers sent, as an e-mail attachment, the proposed timings to the Pharr District. Within a few days, the district implemented these timings at the FM 88 site. The district staff decided to use the proposed Evening-Peak timings for the Morning-Peak period as well. The district staff has informed the researchers that the traffic flow through the system has experienced significant improvement. The following is a summary of observations of TxDOT staff:

- Shorter cyclic queues at the exterior approaches,
- Shorter cyclic queues at the interior approaches, and
- Good arterial progression.

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APPENDIX A. SURVEY QUESTIONAIRE

TEXAS TRANSPORTATION INSTITUTE

Project 7-4913

SURVEY OF CURRENT PRACTICES FOR OPERATING AND EVALUATING SIGNALIZED DIAMOND INTERCHANGES

The Texas Transportation Institute is conducting a research project entitled *Operational Strategies for Arterial Congestion at Interchanges*. One objective of this project is to develop user-friendly, systematic procedures and guidelines for analyzing and improving the existing operations of a diamond interchange in close proximity to an adjacent traffic signal on an arterial. The purpose of the guidelines is as follows: 1) to assess the type, extent, causes and severity of operational problems, and 2) to establish how many signals to coordinate with the interchange. In order to develop the guidelines, one task is to survey the TxDOT districts and cities to find out the current procedures and processes for analyzing and improving operations of congested diamond interchanges. Please take a few minutes to complete this survey with the best information available and return it to the address on the last page. If you have any questions about the survey or need any additional information, please contact Kevin Balke at (409) 845-9899 or Nadeem Chaudhary at (409)845-9890.

1. How often do you evaluate the operations of the diamond interchanges in your district?

   ___ On an as needed basis _____ Once every year _____ Every 1-3 years ___Every 3-5 years

2. Listed below are common objectives of operating the signals at diamond interchanges. Please rank in priority order (1 being the top priority, 7 being the last priority) that you follow for operating diamond interchanges in your district.

   _______ Prevent queues on the frontage road from interfering with exiting ramp traffic
   _______ Maintain good progression on the arterial street
   _______ Prevent queues internal in the interchanges from blocking upstream intersections
   _______ Balance delays on external approaches to the interchange
   _______ Provide access to properties adjacent to the interchange
   _______ Prevent queues from adjacent signalized intersection from blocking interchange intersections
   _______ Prevent queues for interchange intersections from blocking adjacent signalized intersection

3. What techniques would you generally employ when evaluating the operations of diamond interchanges in your district? (Please check all that apply.)

   ___ Field Observations
   ___ Automatic Traffic Volume Counts
   ___ Computer Simulation
   ___ Other (Please specify)
   ___ Manual Turning Movement Counts
   ___ Computer Optimization

4. What simulation/evaluation tools do you use to analyze the operation of the diamond interchanges in your district? (Please check all that apply.)

   ______ Highway Capacity Manual/Highway Capacity Software
   ______ PASSER II
   ______ PASSER IV
   ______ NETSIM/CORSIM
   ______ Others (Please List)
   ______ PASSER III
   ______ SYNCHRO
   ______ TRANSYT

5. Under what traffic volume and geometric conditions would you recommend operating a diamond interchange on one-way frontage roads as two separate intersections, each having *two* phases?

6. Under what traffic volume and geometric conditions would you recommend operating a diamond interchange on one-way frontage roads using a three-phase diamond mode?

7. Under what traffic volume and geometric conditions would you recommend operating a diamond interchange on one-way frontage roads using a four-phase diamond mode?

8. How many interchanges do you operate that use the following control strategies?
   - 4-Phase Diamond Operation Only
   - 3-Phase Diamond Operation Only
   - Separate or Dual Controller Operation
   - 4- and 3-Phase Operation alternating during different times of day

9. List any successes you have had using strategies other than what was asked in the previous question.

10. Are most of the diamond interchanges in your district actuated or pretimed? (Please check appropriate response.)

    ______ ACTUATED _________ PRETIMED

    If actuated, please show on the diagram below the typical configuration for the loop detectors used in your district. (Please indicate distances loops are generally placed from stop line).

11. What strategies have you used in your district to correct the following operational problems at diamond interchanges:

a) Queues spill back from one ramp intersection through the other intersection?

b) Queues from a left-turn lane extends into a through lane?

c) Queues from the frontage road signal blocks the off-ramp?

d) Queues from a frontage road signal backs into an adjacent signalized intersection on the arterial?

e) Queues from an adjacent signalized intersection on the arterial backs into the frontage road signal?

12. What special controller features (such as conditional servicing, detector switching, phase reversals, protective/permissive left-turn phasing, etc.) have you used to address specific operational issues at diamond interchanges? Please discuss the problems and how the controller features were used.

13. In your opinion, what type of adjacent intersection has a greater impact on the operations of the interchange when it is in close proximity to the diamond?

______ Three-way (or "T") ______ Four-way with quad lefts _____ About the same

14. What kind of access restrictions have you implemented in your District to correct operational deficiencies at or near diamond interchanges? (Check all that apply.)

_______ None
_______ Rechannelized Driveway
_______ Other (Please specify) .

_______ Prohibited Left-Turns
_______ Installed Traffic Signal

15. What are the average and highest cycle lengths you operate from all the diamond interchanges you operate?

Period	Average Cycle Length (sec)	Highest Cycle Length (sec)
AM Peak		
Off-Peak		
PM Peak		

16. Do you use any special timing plans at any of your diamond interchanges to accommodate special event traffic (such as holidays, sporting events, etc.)?

______No _______Yes.

If YES, what and why?

17. Please list one to three diamond interchange locations in your district that have signalized intersection in close proximity to the interchange and are currently experiencing operational problems. Please describe their problems.

    a)

    b)

    c)

Contact Name: ____________________ Title: ____________________
Telephone Number: ____________________ District/City: ____________________
Fax Number: ____________________ E-Mail Address: ____________________

Please return the completed survey by January 31, 1999, to the following address:

Kevin Balke, P.E.
Texas Transportation Institute
Texas A&M University
College Station, TX 77843-3135
E-Mail Address: kevin-balke@tamu.edu
Fax Number: (409)845-6254

APPENDIX B. TRAVEL TIME CALCULATIONS

The travel time calculations for the interior link of a diamond interchange assumes an initial speed of zero. If we use this assumption to calculate the travel time from the diamond interchange to an adjacent signal, we may over-estimate the travel time when good coordination exists. This will happen because the vehicles leaving the diamond will be traveling at a certain speed. To obtain a better estimation of travel time in such situations, one must use the vehicular speed at the time it leaves the downstream signal of the interchange. This result can be achieved by using a two step approach described below using the sample system shown in Figure B1:

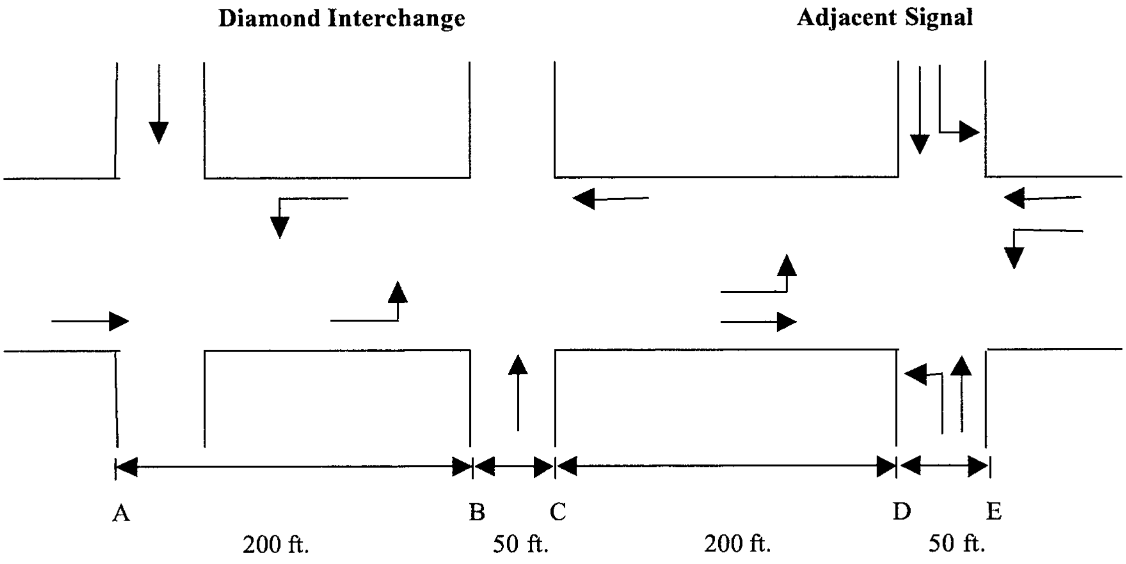

Figure B1. Data for Example Travel Time Calculations.

- Calculate (or obtain) the travel time (t_{Total}) from the left signal of the diamond interchange to the adjacent signal.
- Calculate (or obtain) the travel time (t_D) from the left signal of the interchange to the right signal of the interchange.
- Obtain the interchange to signal travel time (t_{DS}) by subtracting t_D from t_{Total}.

Travel time from the adjacent signal to the diamond interchange will still be calculated with the assumption that vehicles will be stopped at the adjacent signal. Tables B1, B2, and B3 provide travel times for various speeds and travel distances. In the following, we illustrate travel time determination for distance data as shown in Figure B1.

Table B1. Travel Times for 100 to 600 Foot Links.

Design Speed	Distance (ft.)										
(mph)	100	150	200	250	300	350	400	450	500	550	600
20	5	7	9	10	12	14	16	17	19	21	22
25	5	7	8	9	11	12	13	15	16	18	19
30	5	7	8	9	10	11	13	14	15	16	17
35	5	7	8	9	10	11	12	13	14	15	16
40	5	7	8	9	10	11	12	13	14	14	15
45	5	7	8	9	10	11	12	13	14	14	15

Table B1. Travel Times for 650 to 1150 Foot Links.

Design Speed	Distance (ft.)										
(mph)	650	700	750	800	850	900	950	1000	1050	1100	1150
20	24	26	28	29	31	33	35	36	38	40	41
25	20	22	23	24	26	27	28	30	31	32	34
30	18	19	20	22	23	24	25	26	27	28	30
35	17	18	19	20	21	22	23	24	25	26	27
40	16	17	18	19	20	20	21	22	23	24	25
45	16	17	17	18	19	20	20	21	22	23	23

Table B2. Travel Times for 1200 to 1700 Foot Links.

Design Speed	Distance (ft.)										
(mph)	1200	1250	1300	1350	1400	1450	1500	1550	1600	1650	1700
20	43	45	47	48	50	52	53	55	57	59	60
25	35	36	38	39	41	42	43	45	46	47	49
30	31	32	33	34	35	36	38	39	40	41	42
35	28	29	30	31	32	33	34	35	36	37	38
40	25	26	27	28	29	30	31	31	32	33	34
45	24	25	26	26	27	28	29	29	30	31	32

For this example, we assume a design speed of 30 mph. From Figure B1, we see that the distance from the distance between the two intersections of the diamond interchange is 200 feet. Also, the distance between the diamond interchange and the adjacent signal is 250 feet. Thus, the total distance from the left intersection of the interchange to the adjacent signal is 450 feet. Now we can obtain travel times using the above tables.

First, we consider the eastbound traffic. From Table B1, we find that t_{Total} is 14 seconds (30 mph maximum speed and 450 foot travel distance), and t_D is 8 seconds (30 mph speed and 200 foot travel distance). Therefore, the eastbound travel time from the diamond interchange to the adjacent signal, t_{DS}, is 6 seconds (14 minus 8 seconds). Note that this method is only applicable when there is no queue at the interior through approach.

For the westbound traffic, the travel time from the adjacent signal to the right signal of the diamond interchange is 9 seconds (30 mph speed and 250 foot travel time). Assuming that side-street traffic from the upstream signal will be queued at the right signal of the interchange, the traffic time from the right signal to the left signal of the diamond interchange is determined by the traditional way. In this case, it is 8 seconds (30 mph speed and 200 foot link).