

1. Report No. FHWA/TX-92/1148-4F		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle STRATEGIES FOR IMPROVING TRAFFIC OPERATIONS AT OVERSATURATED DIAMOND INTERCHANGES				5. Report Date March 1992	
				6. Performing Organization Code	
7. Author(s) G. Curtis Herrick and Carroll J. Messer				8. Performing Organization Report No. Research Report 1148-4F	
9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135				10. Work Unit No.	
				11. Contract or Grant No. Study No. 2-18-88-1148	
12. Sponsoring Agency Name and Address Texas Department of Transportation Transportation Planning Division P.O. Box 5051 Austin, Texas 78763				13. Type of Report and Period Covered Final-September 1987 March 1992	
				14. Sponsoring Agency Code	
15. Supplementary Notes Research performed in cooperation with DOT, FHWA. Study Title: Guidelines for Operational Control of Diamond Interchange.					
16. Abstract <p>This is the fourth and final report conducted within research project 1148 entitled "Guidelines for Operational Control of Diamond Interchanges" conducted by Texas Transportation Institute for Texas Department of Transportation within its HR&P research program. The four reports are:</p> <ol style="list-style-type: none"> 1. A National Survey of Single-Point Urban Interchanges. 2. Traffic Signal Timing Models for Oversaturated Signalized Interchanges. 3. An Applications Manual for Evaluating Two-and Three-Level Diamond Interchanges. 4. Strategies for Improving Traffic Operations at Oversaturated Diamond Interchanges. <p>Interested readers may wish to acquire this entire series of reports from the Texas Transportation Institute. In addition, NCHRP 345 is a highly recommended complementary source document. This final report (1148-4F) contains recommended strategies for improving traffic operations at signalized diamond interchanges that are becoming oversaturated (i.e., have demand volumes exceeding phase capacity) for periods of time during the peak rush hours of the day. This problem is expected to grow worse with time as traffic was found to increase at about 3.2% per year in the six largest Texas cities. Enhanced features for third-generation traffic control are also recommended for consideration in future specification updates of diamond controllers. Traffic signal manufacturers may also wish to examine these new features as the operational need for them is rising. In addition, enhanced traffic detector strategies are also provided to identify the presence of queue backups onto the freeway drive oversaturated conditions.</p>					
17. Key Words Dynamic optimization model, signalized interchanges TRAF-NETSIM, diamond interchange.			18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service 5285 Port Royal Road. Springfield, VA 22161		
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of Pages 74	
				22. Price	

**STRATEGIES FOR IMPROVING TRAFFIC OPERATIONS
AT OVERSATURATED DIAMOND INTERCHANGES**

by

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**Research Report 1148-4F
Research Study No. 01-31-92-1148
Study Title: Guidelines for Operational Control of Diamond Interchanges**

Sponsored by the

Texas Department of Transportation

March 1992

**TEXAS TRANSPORTATION INSTITUTE
The Texas A&M University System
College Station, Texas 77843-3135**

METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	2.54	centimetres	cm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km

AREA				
in ²	square inches	645.2	centimetres squared	cm ²
ft ²	square feet	0.0929	metres squared	m ²
yd ²	square yards	0.836	metres squared	m ²
mi ²	square miles	2.59	kilometres squared	km ²
ac	acres	0.395	hectares	ha

MASS (weight)				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg

VOLUME				
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft ³	cubic feet	0.0328	metres cubed	m ³
yd ³	cubic yards	0.0765	metres cubed	m ³

NOTE: Volumes greater than 1000 L shall be shown in m³.

TEMPERATURE (exact)

°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C
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APPROXIMATE CONVERSIONS TO SI UNITS

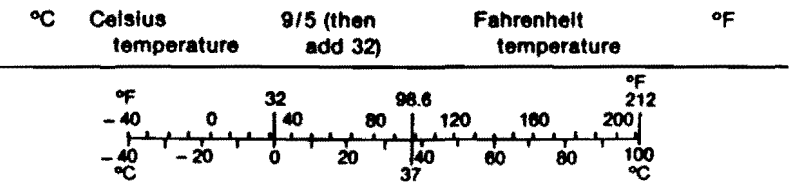
Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi

AREA				
mm ²	millimetres squared	0.0016	square inches	in ²
m ²	metres squared	10.764	square feet	ft ²
km ²	kilometres squared	0.39	square miles	mi ²
ha	hectares (10 000 m ²)	2.53	acres	ac

MASS (weight)				
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T

VOLUME				
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m ³	metres cubed	35.315	cubic feet	ft ³
m ³	metres cubed	1.308	cubic yards	yd ³

TEMPERATURE (exact)



These factors conform to the requirement of FHWA Order 5190.1A.

* SI is the symbol for the International System of Measurements

ABSTRACT

This is the fourth and final report conducted within Research Project 1148 entitled "Guidelines for Operational Control of Diamond Interchanges" conducted by Texas Transportation Institute for Texas Department of Transportation within its normal Highway Planning and Research (HP&R) research program. The four reports are entitled:

1148-1. A National Survey of Single-Point Urban Interchanges,

1148-2. Traffic Signal Timing Models for Oversaturated Signalized Interchanges,

1148-3. An Applications Manual for Evaluating Two- and Three-Level Diamond Interchange Operations, and

1148-4. Strategies for Improving Traffic Operations at Oversaturated Diamond Interchanges.

Interested readers may wish to acquire this entire series of reports from the Texas Transportation Institute (TTI). In addition, recently published NCHRP 345 and written by TTI, is a highly recommended complementary source document.

This final report (1148-4F) contains recommended implementation strategies for improving traffic operations at signalized diamond interchanges that are becoming oversaturated (i.e., have demand volumes exceeding phase capacity) and experiencing severe congestion for extended periods of time during the peak rush hours of the day. This operational problem is expected to continue to grow worse with time as freeway traffic was found to be increasing about 3.2% per year in the six largest cities in Texas. The report also provides traffic detector layouts to identify the presence of queue backups onto the freeway during oversaturated conditions.

The performance of several practical signal control strategies for diamond interchanges was assessed over a wide range of traffic volume levels. Three-phase and four-phase-with-overlaps signal phasing strategies were examined and evaluated using the TEXAS

Model based on timings generated using PASSER III. Additionally, queue length estimates were obtained using PASSER II. Research results from this study combined with those obtained previously in report 1148-2 clearly demonstrated the potential benefits of queue management as a desirable control objective during oversaturated conditions.

Enhanced features for third-generation traffic control are also recommended for consideration in future specification updates of urban diamond interchange controllers. New traffic control functions and detection features were identified. Traffic signal manufacturers may also wish to provide these new features in future products.

KEY WORDS: Diamond interchange, traffic signals, single-point urban interchange, urban interchange, TUDI, TRANSYT, PASSER, traffic controller.

IMPLEMENTATION

This report contains recommended implementation strategies for improving traffic operations at signalized diamond interchanges that are becoming oversaturated (i.e., have demand volumes exceeding phase capacity). This problem is expected to grow worse with time as traffic was found to be increasing at about 3.2% per year in the six largest cities in Texas. In addition, traffic detection strategies are also provided to identify the presence of any queue backups onto the freeway during oversaturated conditions.

The proposed enhanced features for third-generation traffic control are also recommended for consideration during future specification updates of diamond interchange traffic controllers. Traffic signal manufacturers may also wish to examine these new features as the operational need for them in the field is rising. Likewise, traffic detector manufacturers may use the ideas noted in this report to develop new multi-function traffic control sensors for applications with the above enhanced controllers.

ACKNOWLEDGEMENTS

The research reported herein was performed as a part of a study entitled "Guidelines for Operational Control of Diamond Interchanges." This study was conducted by the Texas Transportation Institute for the Texas Department of Transportation in cooperation with the U.S. Department of Transportation, Federal Highway Administration. Dr. Carroll J. Messer of the Texas Transportation Institute served as research supervisor. Ms. Karen Glynn of the Texas Department of Transportation, D-18TM in Austin, effectively served as the technical coordinator during the time when most of this research was conducted. Ms. Elizabeth Escamilla was the Word Processor Operator for this report.

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the opinions, findings, and conclusions presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration or the Texas Department of Transportation. This report does not constitute a standard, specification, or regulation. Additionally, this report is not intended for construction, bidding, or permit purposes. Dr. Carroll J. Messer, P.E. #31409, was the engineer in charge of the project.

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1.0 INTRODUCTION

1.1 PROBLEM STATEMENT

Roadway congestion in many urban areas across the nation is generally considered to be increasing. According to a recent study, Hanks and Lomax (1) found the problem of urban traffic congestion in two urban areas in Texas to be ranked in the top half of United States urban areas with the most severe congestion levels. Houston ranked in the top ten and Dallas was seventeenth. The report also stated that there was a much greater dependence on the freeway system in Texas than in any other state in the Southwestern region. This would indicate a need to deal with increasing congestion on urban freeways and principal arterial street connections in Texas. A recent study by Herrick (2) of traffic demand in six Texas cities found that the average urban freeway daily traffic was growing at 3.2% per year. This growth would suggest that traffic demand would double in 22 years.

In Texas urban areas, the primary transfer point between the freeway system and the principal arterial street system is at signalized diamond interchanges. The increasing traffic demand at diamond interchanges is contributing to the degradation of performance. The existence of frontage roads in the urban environment further complicates the operational problem at diamond interchanges, as high volume through movements occurring during freeway incidents must also be satisfied. The operational integrity of the entire urban freeway network could ultimately become compromised if congestion at diamond interchanges continues to increase. Therefore, increasing the efficiency of diamond interchange operations is of primary concern in the face of increasing urban congestion.

As urban centers in Texas continue to experience growth in travel demand, budgetary constraints dictate the more efficient use of existing highway facilities (3). Traditional approaches to signalized diamond interchange operations work very well for undersaturated conditions; however, these methods become inefficient as traffic volumes increase beyond the point of saturation. In order to meet the future challenge of improving operational

efficiency at oversaturated urban diamond interchanges, the traffic engineer needs better technology and improved control strategies to more effectively address the problems.

1.2 STUDY BACKGROUND

Traffic congestion forms at diamond interchanges when the traffic demand exceeds the signal capacity of the interchange. In extreme cases of congestion, excessively long queues of vehicles will be stopped at the signals and the motorists will experience correspondingly long delays while they are processing through the interchange. In some cases, particularly in highly oversaturated cases, ramp queues from the interchange may become so long that they create further congestion by backing onto the freeway mainlanes, thereby causing major freeway congestion and traffic safety problems.

Operational problems are sometimes caused by deficient geometric capacity provided by the existing diamond interchange design. Traffic growth may now exceed the design capacity of the interchange and a more efficient type of diamond interchange is needed. TxDOT design engineers in several large urban districts are faced with a wide variety of needs to increase interchange or intersection capacity within restricted rights-of-way.

The three most common types of basic urban diamond interchanges are the conventional tight urban diamond (TUDI), the split diamond, and the three-level box diamond. Figure 1 illustrates these three basic interchange types with one-way frontage roads. To improve access and mainline flow, the exit and entrance ramp sequence with the frontage roads may be reversed, and the diamond shape becomes an X-shaped interchange. Operational benefits of these changes may also occur within the interchange signal system.

As operational experience has been gained on freeways and interchanges of the interstate highway system during the 1970's and 1980's, experimentation with other diamond-type interchanges has occurred in the United States. This action grew out of the recognition that improved geometrics and signalization could achieve increased capacity and safety at

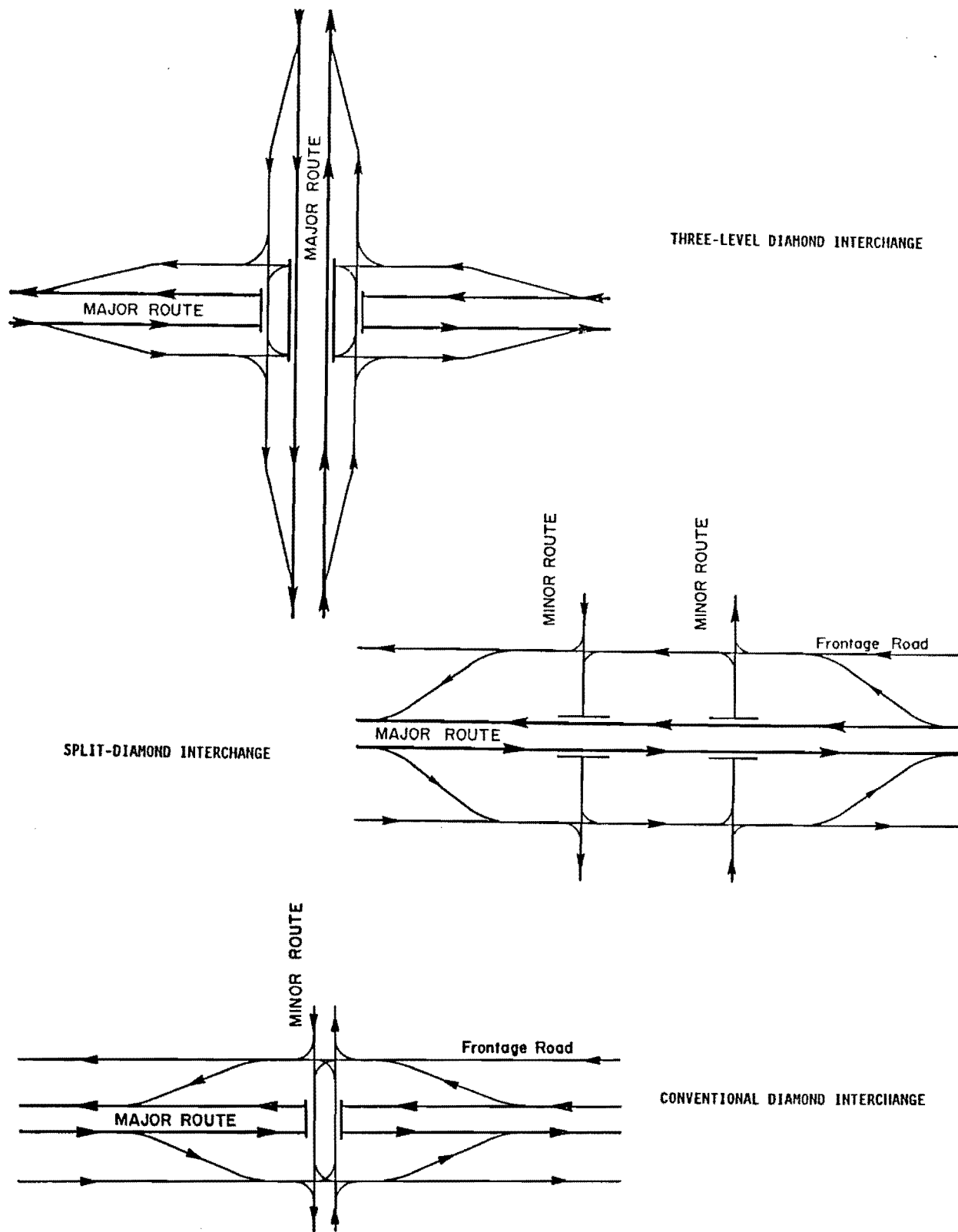


Figure 1. Typical Diamond Interchange Configurations.

some existing interchanges under some as yet unspecified conditions. During the past few years, three new types of urban diamond interchanges have evolved: the single-point urban interchange (SPUI), the three-point diamond, and the three-level stacked diamond. Figure 2 presents schematics of these three types of new diamond interchanges.

To satisfy the ever growing traffic demand, the new types of interchanges are seriously being considered for application in Texas. In one district, numerous three-level box diamonds are proposed for one freeway with possible intermediate upgrade to a three-level stacked diamond, before final upgrading to the "ultimate" design of a five-level directional interchange with interlaced continuous frontage roads.

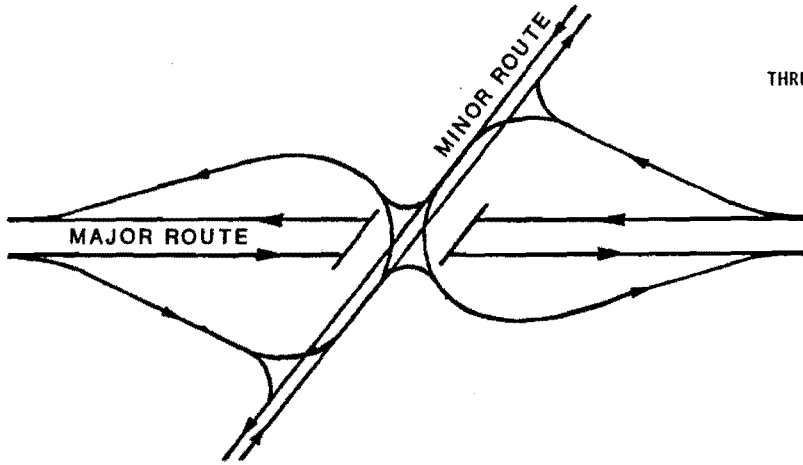
When this research study began, there was only minimal literature (4, 5) and almost no analytic procedures available for efficiently analyzing the capacity of all of these new interchange types, especially where one-way frontage roads are present, as in Texas. Consequentially, engineers sometimes were uncertain whether their proposed interchange design, costing perhaps \$10,000,000 or more, was the most cost-effective alternative.

1.3 RESEARCH OBJECTIVES

The principal research objectives of Study 1148 were to develop procedures for identifying, evaluating, and selecting the optimal design and signal control strategy for the following five types of signalized diamond interchanges for Texas design conditions under both undersaturated and oversaturated traffic:

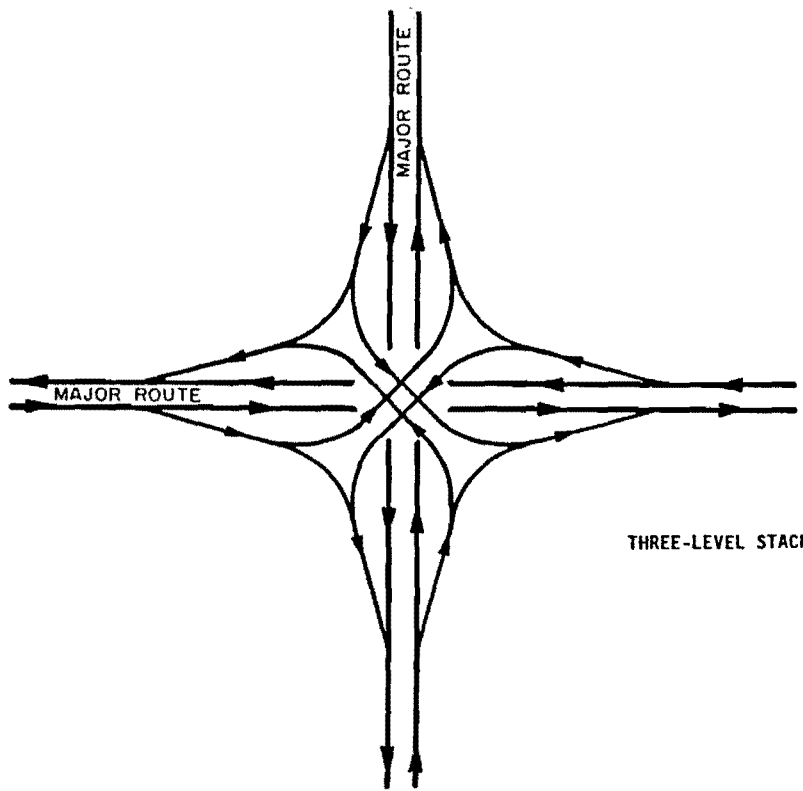
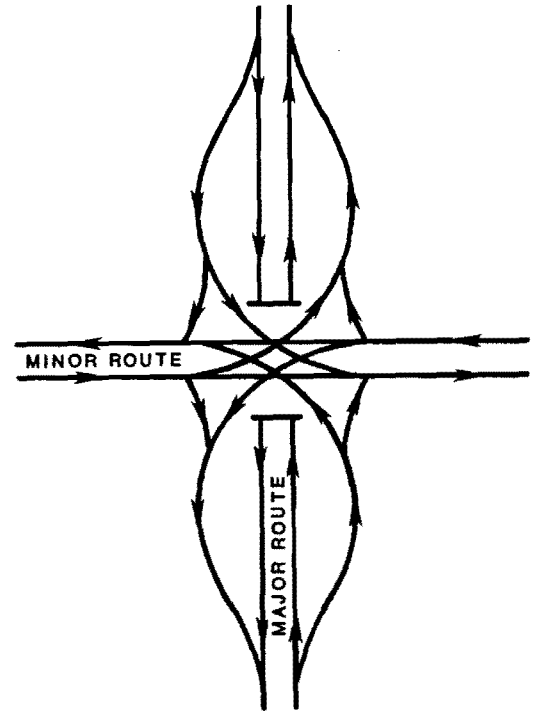
1. conventional tight urban diamond,
2. single-point urban diamond,
3. split-diamond,
4. three-level box diamond, and the
5. three-level stacked diamond.

Consideration was given to the following research guidelines: 1. use existing technology to the extent possible, 2. provide maximum operational capacity, 3. try to minimize traffic



THREE-POINT DIAMOND INTERCHANGE

SINGLE-POINT URBAN INTERCHANGE



THREE-LEVEL STACKED DIAMOND INTERCHANGE

Figure 2. New Diamond Interchange Configurations.

delays as much as possible, 4. avoid conditions that may lock up the interchange, and 5. avoid queueing of vehicles onto the freeway. Clearly, the research objectives were both broad and complex. However, the need to satisfy them in a cost-effective manner was evident. Consequently, a four-year research program entitled "Guidelines for Operational Control of Diamond Interchanges" was approved by TxDOT to address this need.

1.4 RESEARCH PROGRAM

The research methods used varied depending on the phase of the study and the findings developed as the study progressed. Since there were no single-point urban interchanges (SPUIs) in Texas, a field trip was organized to study them in several states. In addition, a survey to inventory and characterize all types of diamond interchanges found in Texas was conducted during the overall field inventory activity. A project report entitled "A Nationwide Survey of Single Point Urban Interchanges" was published as Report 1148-1 (6). This early study activity lead the research team to conduct a national study on SPUIs which has been recently published as NCHRP 345 (7). Readers are encouraged to peruse this document as if it were a part of Study 1148, for in NCHRP 345 one will find an extensive upgrade to 1148-1 plus numerous design and operational guidelines for SPUIs and comparisons to tight urban diamond interchanges (TUDIs). Consequently, no attempt has been made to duplicate the details of that report herein.

One focus area of Study 1148 was to assess the operational nature of TUDIs during high-volume conditions that might lead to oversaturated capacity conditions. In addition, traffic control strategies, both practical and theoretical, were identified and evaluated. Two reports have been prepared by the research team on this subject. One report assessed the traffic actuated traffic control strategy used by the City of Arlington, Texas (8). This study was primarily based on field observations of queueing delays related to traffic volumes and phase generation. The Arlington system will generate phasing sequences from two-phase to four-phase, depending on the detection of queues on the various approaches by special queue detectors installed beyond those normally used for traffic actuated control.

Permissive left turns are encouraged by this system. One may wish to obtain Reference 8 for more details on this study. In the second report, an effective but somewhat complex theoretical control strategy for oversaturated diamonds was developed using mixed-integer linear programming, programmed for optimization using the commercial package LINDO, and assessed using the microscopic simulation program NETSIM. This study report was published as Report 1148-2 (9).

At the outset of Study 1148, the original plan was to develop a new code for timing and evaluating all types of diamond interchanges that would be a part of the PASSER III family of programs (10). However, after successfully using the new microcomputer version of TRANSYT-7F about one year into the study, it became evident to the research team that the original plan was not the optimal plan, and that efforts should be devoted to developing an effective applications manual for using TRANSYT-7F to evaluate all forms of signalized diamond interchanges at issue in Texas. Initial efforts discovered several coding errors in the early versions of TRANSYT-7F, Release 6, and these findings delayed both the delivery of updated versions of Release 6 as well as the applications manual, which has now been completed as Report 1148-3. This report is currently in the review process for publication (11). All interchange forms outlined in the research objectives are covered in this users manual for TRANSYT-7F, Release 6.3. Example problems are coded and evaluated.

This final report for Study 1148, Report 1148-4F, specifically addresses the practical problem of traffic control at diamond interchanges during oversaturated traffic conditions. The assessment covers the two traffic signal control strategies commonly used for conventional tight urban diamond interchanges (TUDIs) in Texas. Two control strategies, three-phase and four-phase with two overlaps, are the only traffic actuated strategies specified in the latest traffic actuated controller specifications for diamond interchanges released recently (1992) by TxDOT (12). This study also addresses the effects of queue backup during oversaturated traffic conditions. Guidelines are provided for effective queue management during high volumes, as suggested by Report 1148-2, and practical future enhancements are recommended for the new diamond controller specification (12).

2.0 DIAMOND INTERCHANGE CONTROL

2.1 BACKGROUND

The Strategic Mobility Plan for the Texas Department of Transportation (TxDOT) (13) documents increasing trends for various travel demand indicators including population, the number of registered motor vehicles, and the daily-vehicle-miles-travelled in the state over the next twenty years. The state's population was projected to increase by approximately five million people (thirty-two percent). Likewise, an increase of approximately three million registered motor vehicles (twenty-three percent) was forecasted. There was also a prediction that the daily-vehicle-miles-travelled on Texas highways would increase by approximately ninety-two million miles (thirty-two percent). Given these anticipated growth trends, there is a need to more effectively manage the state's transportation network in order to provide for the safe, economical, effective, and efficient movement of people and goods. Therefore, attention should be focused on the reduction of congestion at critical points of congestion in the highway network, the signalized urban diamond interchange. This chapter reviews the literature regarding the characteristics of the urban control strategies for both undersaturated and oversaturated diamond interchanges are reviewed.

2.2 TIGHT URBAN DIAMOND INTERCHANGE

The following sections deal specifically with the geometric and operational characteristics of the tight urban diamond interchange (TUDI), a typically used connection between a freeway facility and a principal arterial street facility. The characteristics of the tight urban diamond interchange are reviewed in this section. The evaluation tools commonly used by traffic engineers to determine the operational characteristics of the diamond interchange are also considered. Finally, descriptions of alternative interchange designs are included, along with some advantages and disadvantages for each form.

2.2.1 Geometric Considerations

The tight urban diamond interchange consists of two individual intersections connecting the urban freeway system frontage roads to the urban principal arterial street system. These closely spaced intersections, comprising the diamond interchange, operate much differently than two isolated intersections (14). Texas urban frontage roads are typically one way and continuous, creating additional unique operating characteristics. The geometrics of a TUDI differ from those of the conventional diamond interchange primarily in the reduced interior spacing between the frontage roads. The conventional diamond interchange can be characterized as having a rather large interior spacing; whereas, the tight urban diamond interchange has a short interior spacing. The details of a typical Texas tight urban diamond interchange with frontage roads is shown in Figure 3.

2.2.2 Simulation Models

A recent study by Radwan and Hatton (15) identified five commonly used computer software packages used in the evaluation of diamond interchanges. These models include: TRANSYT-7F, PASSER II-87, PASSER III-88, NETSIM, and TEXAS. These models are reviewed in this subsection. Three of these models have been updated since the above study: PASSER II-90, PASSER III-90, and TEXAS. The updated models were reviewed below in lieu of the previous versions.

Computer software packages for traffic signal system analysis can generally be classified as either macroscopic or microscopic models. Macroscopic computer models use mathematical expressions to analyze traffic flow on urban streets to determine the system's measures of effectiveness (such as delay, queue, and fuel consumption). These models can carry out either optimization or simulation activities. The optimization option permits a search for the signal timing plan which results in the lowest vehicular delay, while simulation uses predetermined signal settings to assess system performance. Microscopic computer models simulate individual vehicle movements through the street system and update their status in small time increments. These models generally carry out only simulation activities.

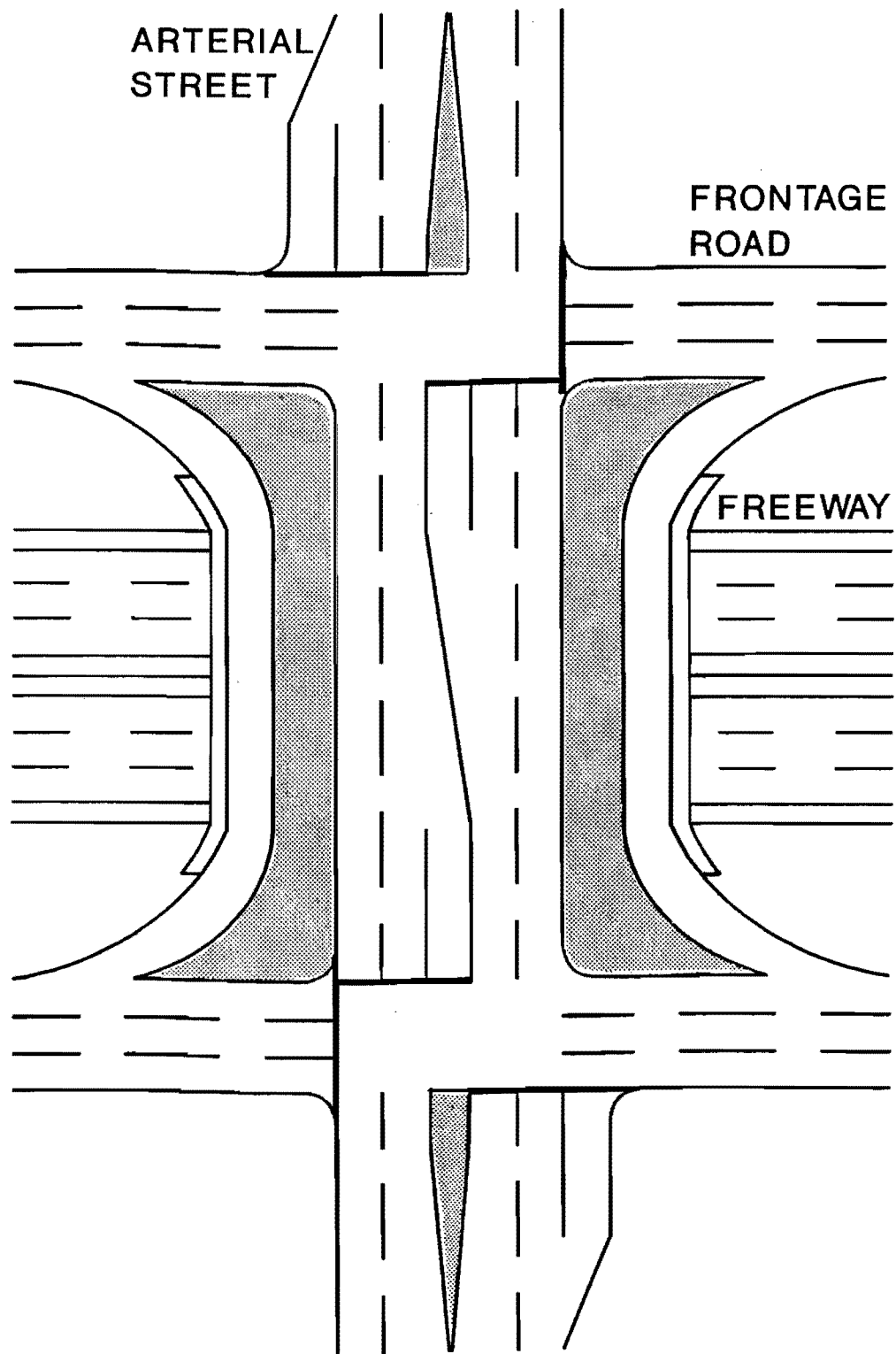


Figure 3. Typical Texas Tight Urban Diamond Interchange.

TRANSYT-7F is the United States version of the Traffic Network Study Tool model originally developed by the Transport and Road Research Laboratory of Great Britain (16). TRANSYT is a macroscopic, deterministic, time-scan model for optimizing traffic signalization on arterials and grid networks. The model uses a link-node arrangement to represent streets and intersections. The optimization procedure in this model is not very useful for evaluating diamond interchanges because it uses a methodology which minimizes delays and stops normally without regard to progression which is usually desired at diamond interchanges. However, the model offers significant simulation features. The model has the ability to simulate individual traffic movements allowing for the inclusion of clearance interval timing and the coding of specific geometric features.

PASSER II-90 is the most recent version of the Progression Analysis and Signal System Evaluation Routine developed by the Texas Transportation Institute for the Texas Department of Transportation (17, 18). PASSER II-90 is a macroscopic, deterministic, optimization model which serves as a tool to assist the traffic engineer in determining optimal traffic signal timings for progression along an arterial using various multi-phase sequences. The model offers advantages of simplicity of data input and the ability to simulate different types of signal phasing schemes. Disadvantages include the aggregation of the through and right-turning movement volumes and the combination of green and clearance intervals, which may be a deficiency with pretimed control.

PASSER III-90 is the most recent version of the conventional diamond interchange model in the Progression Analysis and Signal System Evaluation Routine family of models developed by the Texas Transportation Institute for the Texas Department of Transportation (19, 20). PASSER III-90 is a macroscopic, deterministic, optimization model developed to determine the optimal phase patterns, splits, and internal offsets for signalized conventional diamond interchanges. The model can also optimize system cycle length and progression offsets for diamond interchange systems connected by one-way frontage roads. The advantages and disadvantages of this model are similar to those of PASSER II-90, with the exception of the ability separate the right-turning movements from the through movements.

TRAF-NETSIM is a microscopic simulation model for surface street networks developed for the Federal Highway Administration (21). The model uses a link-node arrangement to represent streets and intersections. The model simulates individual vehicles moving through the system using stochastically determined turning movements and deterministic car following algorithms. The most recent version of TRAF-NETSIM can produce both static and dynamic representations of traffic movements. The model offers several advantages including the ability to simulate a variety of intersection geometries, the graphical presentation of the system provides the ability to check the configuration of the network and the effectiveness of the control strategy, and the ability to manipulate embedded data to represent observed field data. Disadvantages of the TRAF-NETSIM model include the inability to simulate vehicular movement through the intersection, the collection of system performance characteristics rather than each movement, and the inability to change the vehicle arrival pattern.

The TEXAS Model, Traffic Experimental and Analytical Simulation model, was developed by the Center for Transportation Research for the Texas Department of Transportation (22). The TEXAS Model is a microscopic simulation program which can be used to evaluate any isolated intersection or conventional diamond interchange controlled by stop signs, yield signs, or traffic signals. The model simulates individual vehicles moving through the system using stochastically determined turning movements and deterministic car following algorithms. The model also includes an animation option for a visual representation of the control strategy. Limitations of this model include the inability to link intersections and interchanges into networks, the inability to adequately model certain geometric and operational characteristics such as grades and pedestrian conflicts, and poor graphics quality of the animation option.

Each of the previously described evaluation tools offers distinct advantages and disadvantages. The results of each of these models can vary significantly, with some models yielding more realistic results for certain applications (4). Therefore, the limitations of each

model must be considered so that the model will yield realistic results for the traffic conditions being evaluated.

2.2.3. Alternative Diamond Interchange Designs

Reconstruction of major urban freeways will become inevitable as the future as these facilities reach the end of their useful life. This reconstruction will be brought about for a variety of reasons. These reasons include increasing vehicular demand, the need to alleviate traffic congestion, and rebuilding facilities due to infrastructure age and degradation. Future emphasis will most likely be placed on providing improvements within existing right-of-way; therefore, consideration should be given to alternative interchange forms. A review of various urban interchange forms will be reviewed in the following paragraphs.

Leisch (23), along with Leisch, Urbanik and Oxley (24), discussed the various urban diamond interchange forms currently used throughout the United States. The more common interchange forms include the conventional diamond interchange, the split diamond interchange, the three-level diamond interchange. More innovative urban interchange forms have been developed in recent years. These newer interchange forms include the single-point diamond, the three-point diamond, and the three-level stacked diamond interchange. These diamond interchange forms were shown in Figures 1 and 2.

The compressed diamond and the tight urban diamond interchange are suitable for use in urban areas. These designs are appropriate for use where low to moderate traffic volumes exist on ramps and where right-of-way is restricted. Generally, these designs are used for connections between a freeway and an arterial or collector street facility.

The split diamond interchange is considered appropriate in central urban areas. These designs can be effectively utilized in areas where multiple arterial streets and frontage roads exist. The capacity of this interchange form is normally high when a pair of one-way streets are used, although, the design is suitable for other applications as well.

The three-level diamond interchange is a high capacity urban interchange form, commonly found in suburban settings. This design is suitable for use at locations where the freeway is interchanging with a high volume arterial street facility. This interchange form seems to work best when access along the arterial street can be restricted for approximately 1000 feet either side of the freeway.

The single-point diamond interchange, first introduced about 20 years ago, is now becoming widely accepted for use due to its compactness. This design seems to work best at locations where continuous frontage roads do not exist and a single three-phase traffic signal can be used (7). An additional traffic signal phase is required to accommodate continuous frontage road through movements which tends to reduce the operational efficiency of this design.

The three-point diamond interchange can be used at locations where traffic volumes are moderate and right-of-way is restricted on two of the four quadrants. This design uses three two-phase signalized intersections, which offers the advantage of having a higher capacity than the single-point diamond interchange with a similar number of lanes. This design works well when the intersections can be spaced 400 to 500 feet apart and the traffic signals can be coordinated. This design is also well suited for heavily skewed locations; however, when the crossing arterial street approaches right angles these advantages may be reduced.

The three-level stacked diamond interchange is a high capacity design which can be accommodated within conventional right-of-way requirements. The design incorporates a single signalized intersection concept to handle conflicting turning movements. This design uses two-phase traffic signal control to achieve greater operational efficiency. Other interesting aspects of this design include opposing left-turning vehicles passing on the left and channelized right-turns being handled with yield control.

2.3 UNDERSATURATED OPERATIONS

The operational characteristics and control of two diamond interchange operational regions were of primary concern to this study. These were the undersaturated region and the oversaturated region. Certainly one could argue that there is a highly volatile transition zone between these regions where some combination of undersaturated and oversaturated operational characteristics exists. For the purposes of this report, the transition zone was not specifically identified in the operational analyses. Inherent in each operating region of capacity, undersaturated and oversaturated, are very unique operating characteristics, which require significantly different methods of traffic control. Therefore, practical control strategies should consider these operational regions to provide the most effective and efficient service.

The most common traffic flow region of diamond interchange operation is the undersaturated region. Traffic demand does not exceed capacity in this region. Congestion levels can be characterized as minimal, occurring for short durations around the peak periods. The desired control objectives for this operational region consists of the minimization of both stops and delays (25). Traditional undersaturated signalized diamond interchange control strategies include three-phase and four-phase-with-overlaps schemes.

2.3.1. Three-Phase Control

The typical three-phase diamond interchange control strategy (26, 27) used in Texas provides for simultaneous movement of the frontage road approaches and the possibility of separate movements for each direction of the arterial street. Phase 1 consists of the simultaneous movement of the frontage road approaches. Phase 2 consists of the concurrent movement of the arterial street approaches. If traffic conditions are appropriate, permissive left-turning movements from the arterial street can be allowed during this phase. Phase 3 consists of the protected arterial street left-turning movements. The phasing sequence for the three-phase control strategy is shown in Figure 4.

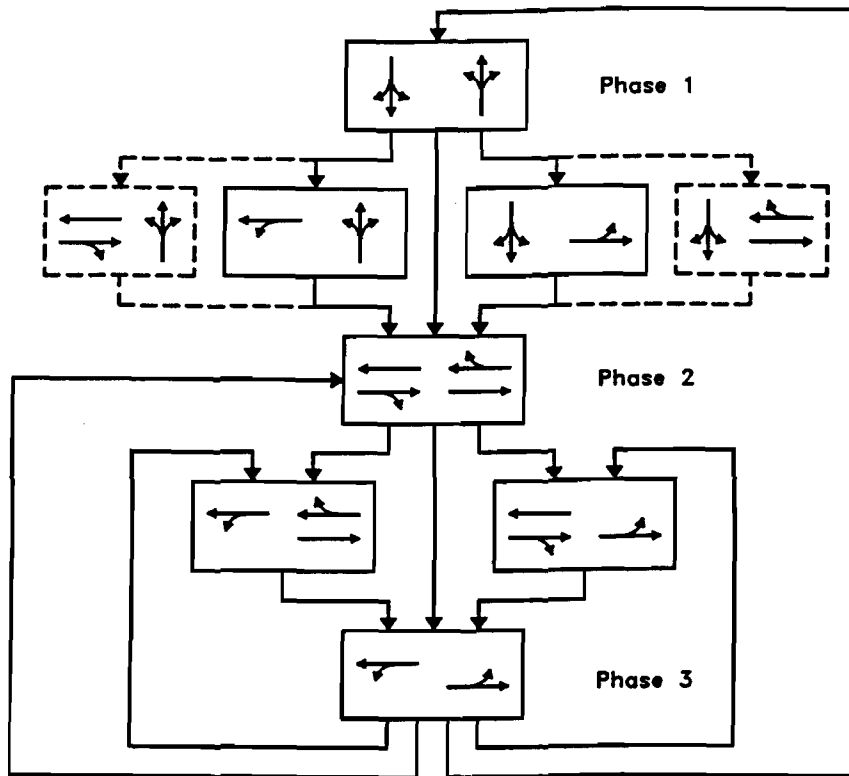


Figure 4. Three-Phase Diamond Interchange Signal Control.

The three-phase control strategy is designed to provide for the four external movements in only two phases. This strategy usually operates at shorter cycle lengths, reducing the delay otherwise incurred with the use of longer cycle lengths. A fewer number of external phases also contribute to lower delays, however, additional stops are incurred in the interchange interior with this control strategy. Three-phase control generally operates better when interchanges are wide and when through movements account for a high proportion of the total traffic flow. The three-phase control strategy generally requires short cycle lengths with wider interior interchange spacings which permits enhanced phase flexibility and smoother traffic flow through the interchange.

Inherent in the three-phase control strategy are problems which may result in a loss of operational efficiency at the diamond interchange. Phase 1 tends to fill the interior of the interchange with vehicles as left-turning vehicles normally must stop at the downstream intersection to allow for the simultaneous servicing of that frontage road approach. The amount of interior queueing increases as the distance between the frontage roads decreases for large left-turning volumes. Three-phase control is also susceptible to "lock-up" during periods of high volumes at smaller diamond interchanges since two output movements from within the interchange can potentially become blocked by long storage queues during each phase.

2.3.2 Four-Phase-with-Overlaps Control

The four-phase-with-overlaps diamond interchange control strategy (26, 27) is generally considered the cornerstone of diamond interchange operations in Texas. The strategy is a variation of the four-phase control strategy which separates each of the external interchange approaches into four individual phases for sequential servicing. Operational efficiency is gained through the overlapping of the two frontage road phases with the two arterial street phases. The phasing sequence for the four-phase-with-overlaps control strategy is shown in Figure 5.

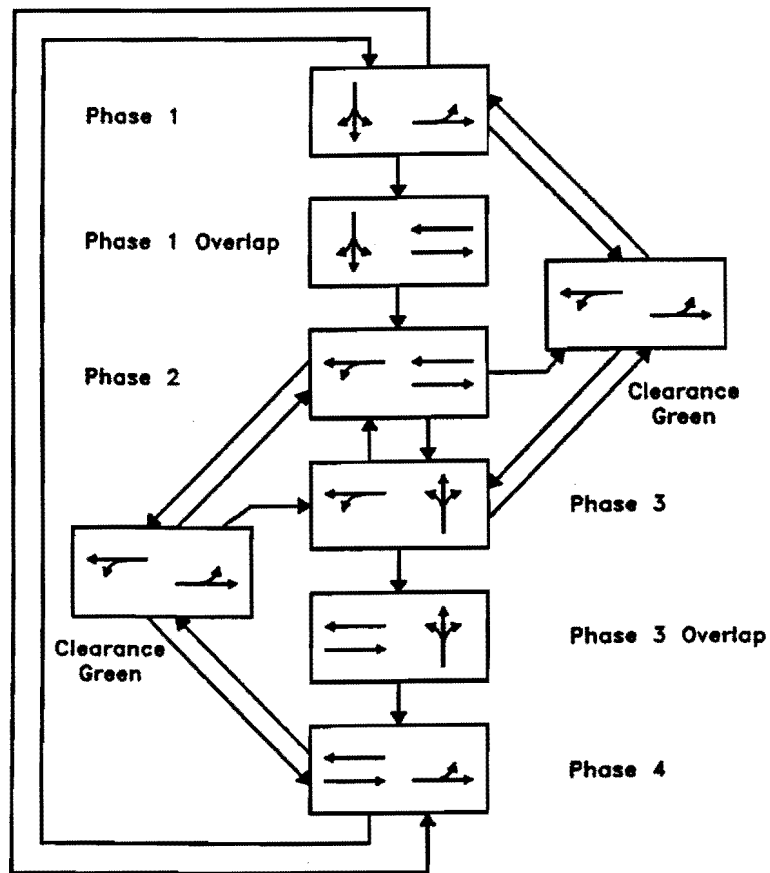


Figure 5. Four-Phase-With-Overlaps Diamond Interchange Signal Control.

The four-phase strategy also offers a reduced number of stops as all external inputs are progressed through the interior of the interchange, with the exception of frontage road U-turning vehicles. The presence of interchange turnarounds negates the need for U-turning vehicles to move through the interchange. Using this design, almost no vehicles are stopped within the interior of the interchange.

The increased number of phases in the four-phase strategy often results in longer cycle lengths producing increased delays. In order to reduce the delay incurred through the use of four-phase control and allow for increased external traffic flow into the interchange, and the frontage road and arterial phases are overlapped. This strategy allows the frontage road approach phase to run concurrently with the arterial approach phase at the opposite intersection for the short period of time required for the arterial traffic to traverse the interior of the interchange before coming into conflict with the frontage road traffic.

The four-phase-with-overlap control is often implemented using double-clearance timers. These double-clearance timers may be located either externally or internally to the controller. The purpose of the double-clearance timer is to extend the frontage road green signal beyond the normal termination point and allow the opposing arterial phase to begin. This provides an overlapping interval where both the frontage road phase and the opposing arterial phase run concurrently for a time no longer than the offset between the two intersections. This feature improves efficiency in diamond interchange operation by allowing the two conflicting movements to move simultaneously.

2.4 OVERSATURATED OPERATIONS

The second region of diamond interchange operation is the oversaturated region. In this region traffic demand exceeds capacity. Congestion levels can be characterized as excessive for long durations, often resulting in gridlock. The desired control objectives for this operational region consist of avoiding queue spillback and providing equitable service to all approaches (25). Traditional diamond interchange control strategies generally provide

ineffective results for oversaturated conditions. Therefore, there is a need to explore new and innovative oversaturated diamond interchange control strategies along with effective transition strategies from undersaturated to oversaturated conditions. This section reviews potential oversaturated diamond interchange control strategies which include the Texas urban diamond signal control, the Arlington approach, and the Kim and Messer approach.

2.4.1 Texas Urban Diamond Signal Control

The Texas urban diamond signal control strategy incorporates both three-phase and four-phase-with-overlaps signal control into a single control unit (26, 27). This control strategy seeks to maximize the benefits of both control strategies. The controller, which is capable of using both three-phase and four-phase-with overlaps control (12), is often referred to as the "Texas Urban Diamond Interchange Controller." The basis for this control strategy lies in the fact that variations in traffic demand may yield improved efficiency with one phase sequence during one part of the day and another phase sequence during another part of the day. The urban diamond controller allows for a change from the three-phase sequence to the four-phase-with-overlaps sequence by time of day. Otherwise, operations are as discussed in previous sections of this thesis. Messer and Chang (26) indicated that the combination of three-phase and four-phase control could efficiently service a wide range of traffic and geometric conditions.

2.4.2 Arlington Approach

The City of Arlington, Texas developed a diamond interchange control strategy which utilizes a dynamic phase selection process based on the detection of critical queue development (8). Two-phase, three-phase, and four-phase sequences can be selected on a cycle-by-cycle basis, based on prevailing traffic conditions. The strategy also attempts to achieve increased operational efficiency by minimizing service to the interior left-turning movements by encouraging permissive left-turn operations. Arlington's innovative approach to diamond interchange traffic signal control appears to offer tremendous flexibility with reasonable operations.

The Arlington system is a traffic responsive system that minimizes service to the interior left-turning movements by incorporating protective/permissive arterial street movements. The system accomplishes phase separation through the use of queue detectors on the interchange's external approaches. During low volume traffic situations the system uses a two-phase control strategy. As traffic demand increases, approach phases are separated to a maximum of four operational phases.

Messer and Chaudhary (8) evaluated the Arlington approach to diamond interchange control in 1989. Their results indicated the additional phases initiated by the activation of the queue detectors may quickly result in "explosive" cycle lengths. The increase in cycle length and the separation of phases both yield increased diamond interchange delays. As a result, this control strategy becomes somewhat ineffective if traffic demand simultaneously increases to the point of saturation on several interchange approaches. However, the Arlington diamond interchange control system provides increased flexibility through its dynamic phase selection process using critical queue detection on the external approaches.

2.4.3 Kim and Messer Approach

In a recent study, Kim and Messer (9) developed a dynamic optimization model to determine the green splits for oversaturated diamond interchanges. This model maximizes system productivity and minimizes system delay for oversaturated diamond interchanges. The model controls queue lengths on the external diamond interchange approaches through efficient and timely signal timing plan changes as the traffic demand changes. The model also minimizes transitional delay which results from frequent changes in signal timing plans.

The dynamic optimization model utilizes mixed integer linear programming techniques to determine the optimal green splits based on the concept of dynamic queue management, given the traffic demand profile for the entire study period. While this technique requires extensive knowledge of the traffic demand profile for the oversaturated diamond interchange, the approach can be used in a practical environment using existing data collection techniques to obtain an average traffic demand profile. Using a

representative traffic demand profile, this procedure can be employed to determine the appropriate signal timing plans for the interchange. The signal timing plans can then be implemented on a time-of-day basis. The major drawback to using this off-line, analytic approach is that any significant variations in the traffic demand profile will render the signal timing plans ineffective. A new traffic demand profile must then be determined and signal timing plans can then be re-evaluated.

As traffic management systems advance to the point of implementation, one could envision the Kim and Messer procedure being used in a real-time traffic management or control environment. The traffic demand profile could be continuously updated in this type of environment. The dynamic model could then be run on a real-time basis to determine the appropriate signal timing plans.

2.5 DIAMOND INTERCHANGE CONTROL SYSTEM ASSESSMENTS

Traffic control strategies have evolved over the past several years. Control strategies began to be implemented through the use of pretimed electro-mechanical controllers, but controllers have recently incorporated technology advancements in the areas of microprocessors and computing abilities. Table 1 presents a summary of the evolution of diamond interchange control systems.

A first generation system can be characterized as pretimed mechanical control system. This control system was designed to require off-line generation and input of various timing parameters by the traffic engineer. These first generation systems performed reasonably well, however, they lacked the ability to adequately respond to variations in traffic demand. In order to compensate for this inability, additional timing plans or "dials" were added on a time of day basis.

Table 1. Diamond Interchange Control System Evolution

<p>Diamond Interchange Control System Technology</p>
<p>GENERATION 1.0 (Past Technology)</p>
<p>Pretimed mechanical control</p> <p>Off-line generation and input of timing parameters</p>
<p>GENERATION 2.0 (Current Technology)</p>
<p>Microprocessor-based control</p> <p>Off-line generation and input of timing parameters</p> <p>Kim and Messer approach could be viewed as a GENERATION 2.5 control system</p>
<p>GENERATION 3.0 (Future Technology)</p>
<p>Goal is to make use of existing traffic conditions and forecasting techniques to provide on-line computation and selection of various timing parameters</p>

A second generation diamond interchange control system is a microprocessor based system designed to require off-line generation and input of various timing parameters by the traffic engineer. However, the second generation control system allows a traffic responsive method of operation. Most of the diamond interchange control equipment in use today makes use of this second generation approach. The Kim and Messer procedure represents a step toward a third generation system and can be characterized as a 2.5 generation approach.

The goal of a third generation system is to make use of existing traffic characteristics and forecasting techniques to provide on-line computation and selection of various timing parameters. The third generation system will require an advanced degree of intelligence in the traffic signal timer and more efficient communications to a computer facility in order to provide for on-line computation and forecasting techniques. Detection systems with a higher degree of accuracy than existing equipment will also be required to adequately measure the existing traffic characteristics to be used as a basis for predicting future traffic demand and computing the various signal timing parameters.

Future diamond interchange control systems should be designed to make maximum use of existing technology. Consideration should also be given to future technological advancements to improve existing equipment. Only then will the industry move closer to a third generation type of control system.

3.0 EXPERIMENTAL DESIGN

This chapter describes the experimental design used for this research. The study first examined the operational performance of undersaturated signalized diamond interchanges for two conventional signal strategies. As traffic performance was noted to deteriorate seriously as volumes approached the point of saturation, optional control strategies were desired to improve performance. Thus, a nationwide telephone survey was conducted to identify alternative control strategies for oversaturated diamond interchanges. Then a second series of simulation studies were conducted to further examine the operational performance of the viable signal control strategies over a range of oversaturated traffic volumes. An evaluation of the alternative oversaturated diamond interchange control strategies was performed. Recommendations were developed from these studies regarding the operational advantages of the identified strategies during high volume conditions.

3.1. EXPERIMENTAL PROTOCOL

The hypothetical signalized diamond interchange shown in Figure 6 was used as a case study to examine traffic performance over a wide range of traffic volume levels. The separation distance between the ramp signals was assumed to be 200 feet, representative of a tight urban diamond interchange. In the first studies, volumes on the approaches were varied to the point of saturation at the diamond interchange. In subsequent simulations, volumes were increased until they exceeded capacity by 20 percent or more.

3.1.1 Signal Strategies

The interchange operational control strategies studied in this research included both the Texas (lag-lag) three-phase strategy and the traditional TTI four-phase-with-overlaps (lead-lead) strategy. The data obtained in this research phase were used with annual growth data of urban freeways in Texas (2) to predict when a diamond interchange might become oversaturated. Estimations of the periods of daily congestion were also made considering the expansion of peak period spreading.

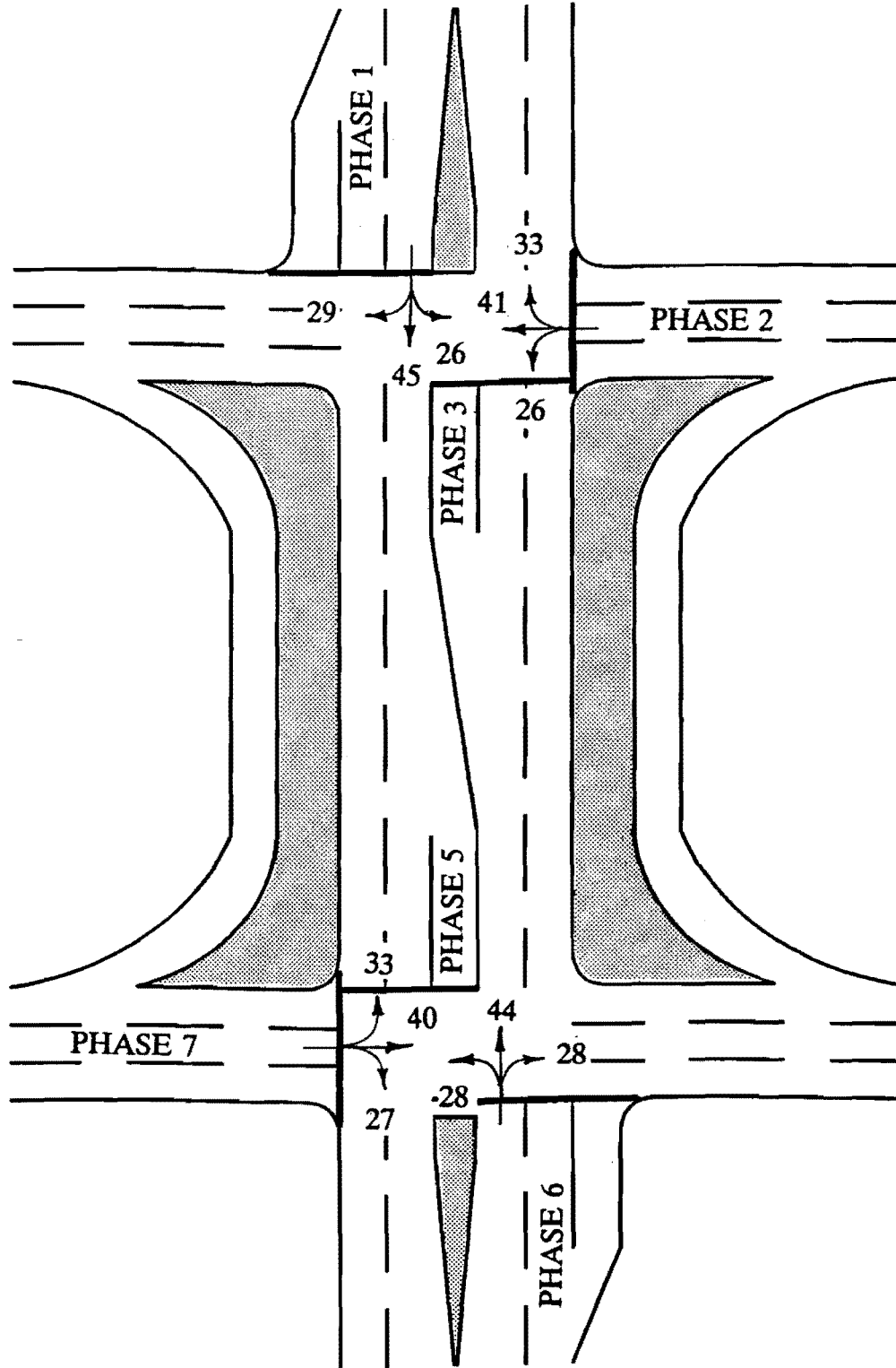


Figure 6. Diamond Interchange Phasing and Turning Movement Percentages.

3.1.2 Study Scenarios

The following traffic volume patterns were studied in the simulations:

- Case 1. Increase the traffic volume only on one side of the interchange;
- Case 2. Increase the traffic volume only on the frontage road approaches;
- Case 3. Increase the traffic volume only on the arterial approaches; and
- Case 4. Increase the traffic volume on all approaches.

The percentage of turning traffic was held constant throughout the increase in traffic volumes as shown in Figure 6.

3.2 ANALYSIS OF TRADITIONAL UNDERSATURATED CONTROL STRATEGIES

This task examined the operational performance of traditional diamond interchange strategies during undersaturated conditions. The urban diamond interchange of Figure 6 was analyzed using the PASSER II-90 and PASSER III-90 microcomputer models. Traffic performance provided by the models included total interchange delay, volume-to-capacity ratio, and queue size. Each of the models perform macroscopic traffic operations analysis useful in the evaluation of undersaturated operational conditions. Since PASSER III-90 does not compute queue length on the interchange approaches, PASSER II-90 was used to estimate queue development with increasing traffic demand. Similar volumes and green splits were used in PASSER II to expedite these surrogate calculations for PASSER III.

3.3 SURVEY OF ALTERNATIVE OVERSATURATED CONTROL STRATEGIES

Following the undersaturated studies, a national survey was conducted to identify alternative strategies for oversaturated conditions. The survey consisted primarily of telephone interviews and some personal interviews with 18 experienced urban traffic engineers. The survey revealed that the traditional three-phase and four-phase-with-overlaps signal strategies were primarily used without written operational guidelines related to volume levels, except that the increasing potential for three-phase systems to lock-up in smaller interchanges is recognized as a limitation of this phasing strategy.

3.4 ANALYSIS OF ALTERNATIVE OVERSATURATED CONTROL STRATEGIES

Selected oversaturated diamond interchange operational strategies identified in this research, which appears to be most promising for practical application, were analyzed using the TEXAS Model microcomputer program to obtain measures of effectiveness such as total delay, volume-to-capacity ratio, and queue development. The TEXAS Model is a microscopic traffic operations analysis tool which can be used to evaluate oversaturated operational conditions. These measures of effectiveness were then compared to the more traditional control strategies to determine if significant advantages could be derived from using alternative oversaturated diamond interchange control strategies compared to traditional control strategies, such as three-phase control and four-phase-with-overlaps. The oversaturated analysis was performed using the maximum external traffic volumes for each of the four cases outlined in the undersaturated analysis, along with the turning movement patterns shown in Figure 6.

3.5 QUEUE MANAGEMENT

The final phase of this research developed a practical strategy to manage queueing along the frontage roads. The objective of queue management is to provide a reduction in queue development on a specific approach at a traffic actuated oversaturated diamond interchange without adversely impacting the operations of the overall diamond interchange. This strategy objective was accomplished through further analysis of the previously described Case 4 data set. A four-phase-with-overlaps control strategy was selected for analysis purposes, over the three-phase control strategy, on the basis of the predominant usage of this control strategy within the state of Texas. The queue management strategy was then analyzed by the TEXAS Model to obtain various measures of effectiveness, including the queue development length on the phase targeted for reduction, maximum queue length on all approaches, and average queue delay per vehicle. Comparisons were then made with the same case analyzed without the queue management strategy.

4.0 OPERATIONAL ANALYSIS OF UNDERSATURATED CONTROL

This chapter presents the results of the operational analysis of traditional diamond interchange control strategies during undersaturated conditions. A comparison of traditional three-phase control and four-phase-with-overlaps control strategies was first conducted. These results were then related to the growth model (2) to provide a forecast of the time remaining before the diamond interchange becomes oversaturated from existing conditions.

4.1 COMPARISON OF TRADITIONAL CONTROL STRATEGIES

This section compares traditional three-phase and four-phase-with-overlaps undersaturated diamond interchange control strategies based on increasing traffic volumes. Using a typical Texas diamond interchange configuration, as previously shown in Figure 5, moderate turning movement traffic volumes were generated. The generated diamond interchange traffic volumes were typical of those which might be encountered in an urban area with moderate growth potential, such as along Interstate Highway 35 in Austin. A constant cycle length of 80 seconds was first chosen for a comparison of the two strategies. Then consideration was given to a range of cycle lengths from 40 to 150 seconds. The PASSER III-90 microcomputer model was used to generate average interchange delay and the volume-to-capacity ratio for each of the four cases outlined in the experimental design of this study. In each case, the volumes were increased to a point where the critical volume-to-capacity ratio is above 1.0.

4.1.1 80 Second Constant Cycle Length

The results of the operational analysis with respect to the various measures of effectiveness are related graphically in Figures 7-10. The results of the Case 1 comparison, are shown in Figure 7, where traffic volumes were increased on only one side of the interchange. Both interchange control strategies appear to yield comparable average delays and volume-to-capacity ratios as exterior volumes are increased, yet the three-phase control strategy is favored. Figure 8 shows the results of the Case 2 comparison, where traffic

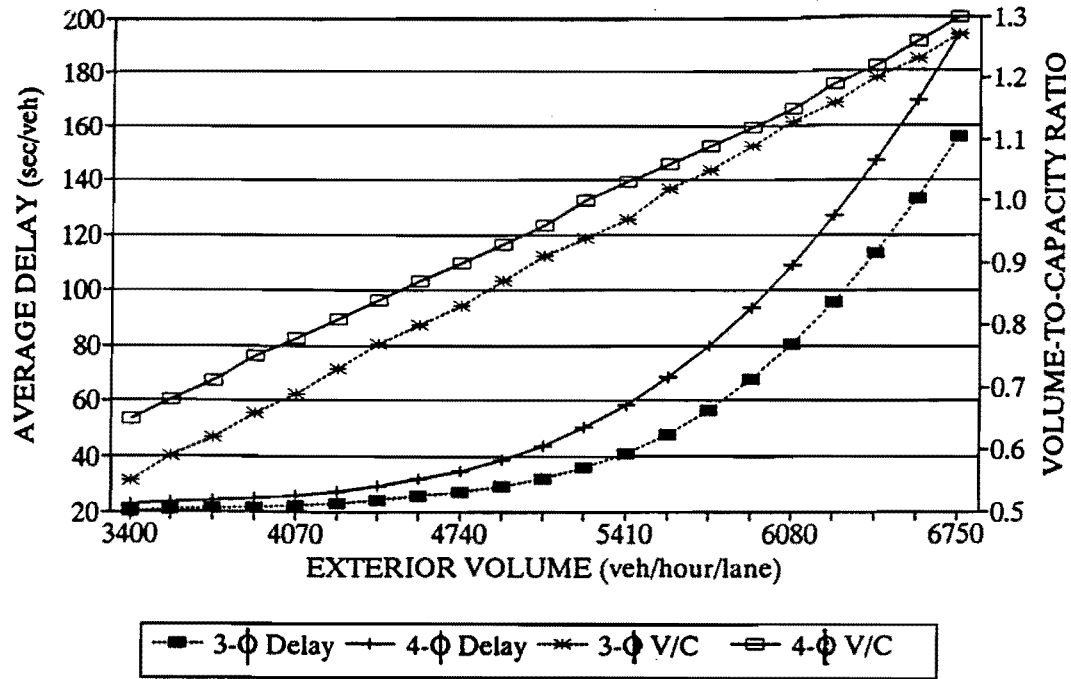


Figure 7. Case 1 Performance Measures.

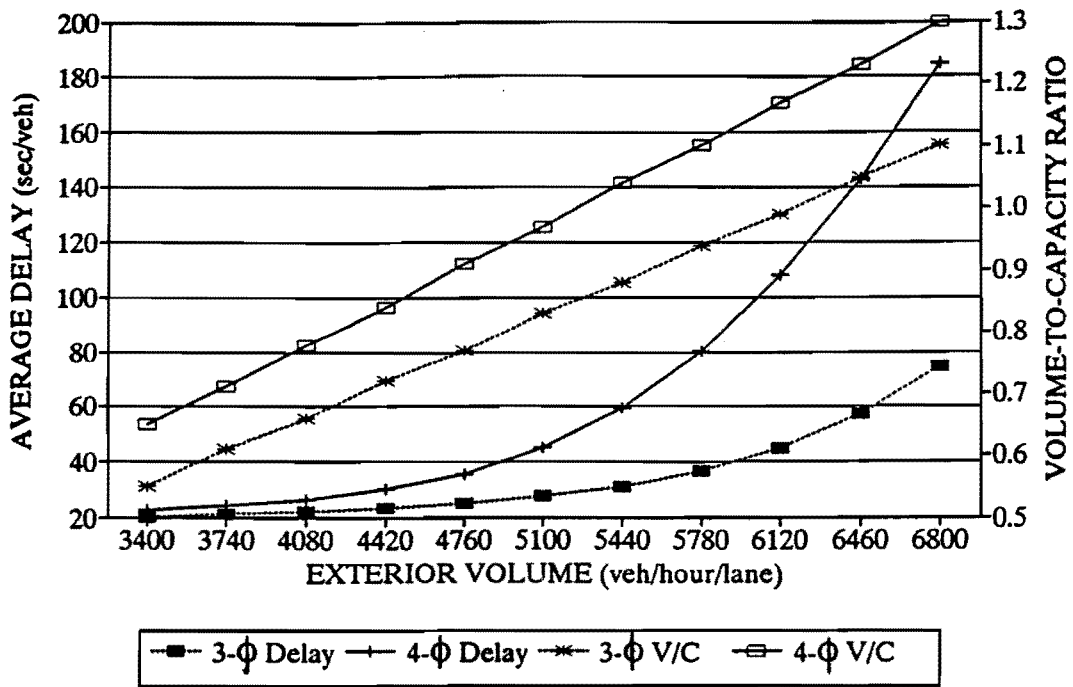


Figure 8. Case 2 Performance Measures.

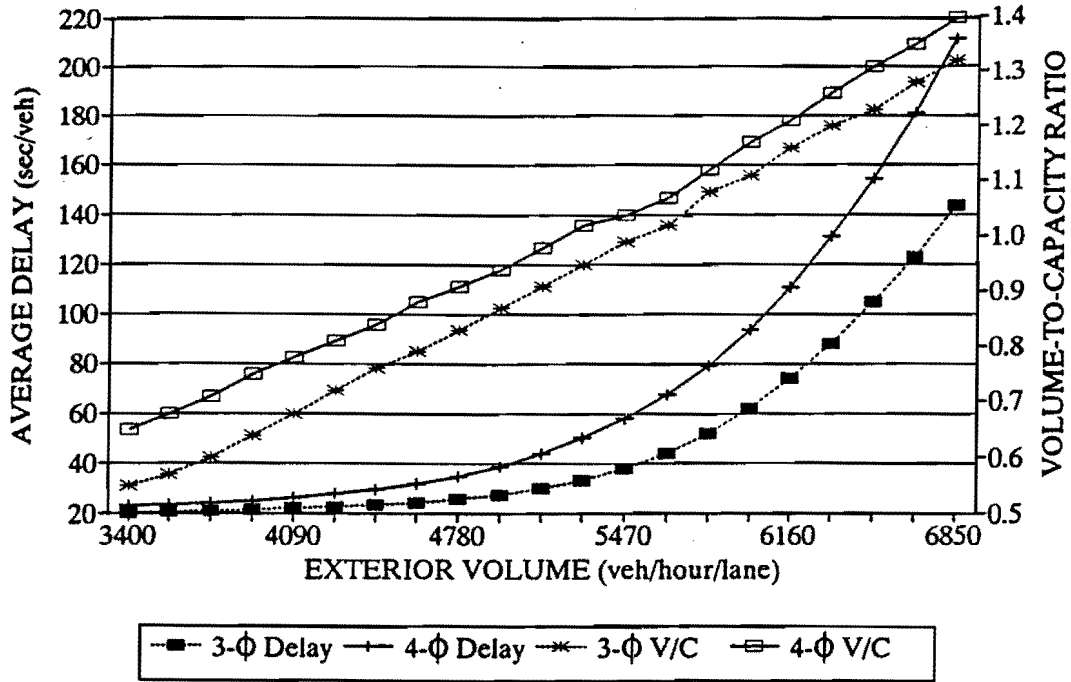


Figure 9. Case 3 Performance Measures.

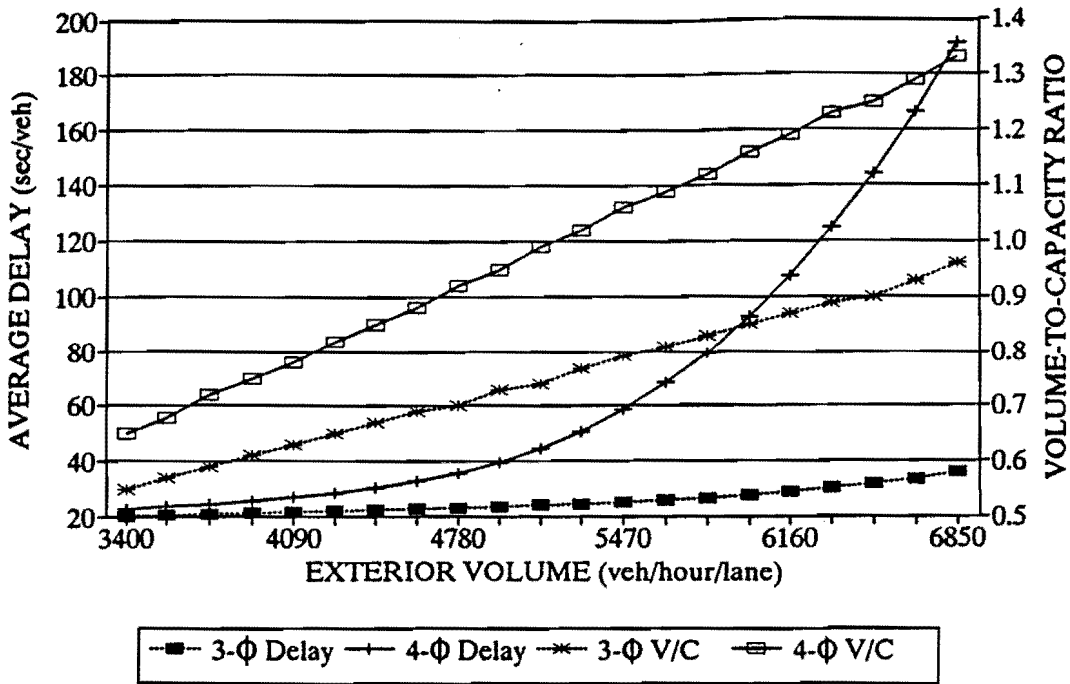


Figure 10. Case 4 Performance Measures.

volumes increased only on the frontage road approaches. Again, the three-phase control strategy produced slightly lower delay. However, a dramatic variation was noted between the volume-to-capacity ratio and the average delay when exterior volumes were increased. Figure 9 shows the results of the Case 3 comparison, where traffic volumes increased only on the arterial approaches. These results were very similar to those of Case 1, with no dramatic variation between the control strategies. Figure 10 shows the results of the Case 4 comparison, where traffic volumes increased on all approaches. These results were similar to those of Case 2, with a substantial variation between the volume-to-capacity ratios and average delay.

The above results indicate that the three-phase diamond interchange control strategy generally performed better than the four-phase-with-overlaps strategy for identical cycle lengths. These results are consistent with field study findings reported by Messer and Chang (26). The comparison of the two control strategies at identical cycle lengths tended to favor the three-phase strategy over the other.

Based on the literature (26), each control strategy should stabilize and operate efficiently at a unique cycle length and this cycle length should be different for the two control strategies considered in this report. In order to demonstrate this point, each case was again analyzed, using PASSER III-90, for arbitrarily selected exterior traffic volume conditions for cycle lengths which ranged from 40 to 150 seconds. In each case, the optimal offset calculated by PASSER III-90 was used in an effort to provide the most efficient signal timing conditions.

4.1.2 Multiple Cycle Lengths

The simulation results of the multiple cycle length analysis are shown in Figures 11-15, with the actual values being tabulated in Reference 2. The results indicate that a unique cycle length exists for some traffic volumes that produces a minimum average delay per vehicle at the interchange, and these minimum delay cycle lengths are indeed different for the three-phase control strategy as compared to the four-phase-with-overlaps control strategy.

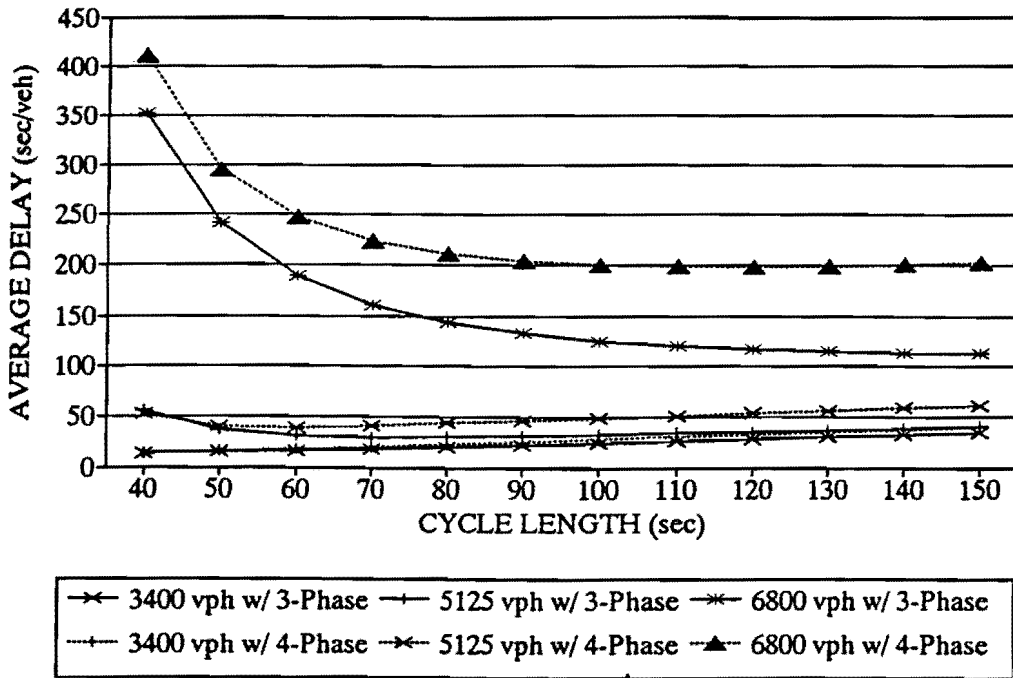


Figure 11. Case 1 Variation in Average Delay with Respect to Cycle Length.

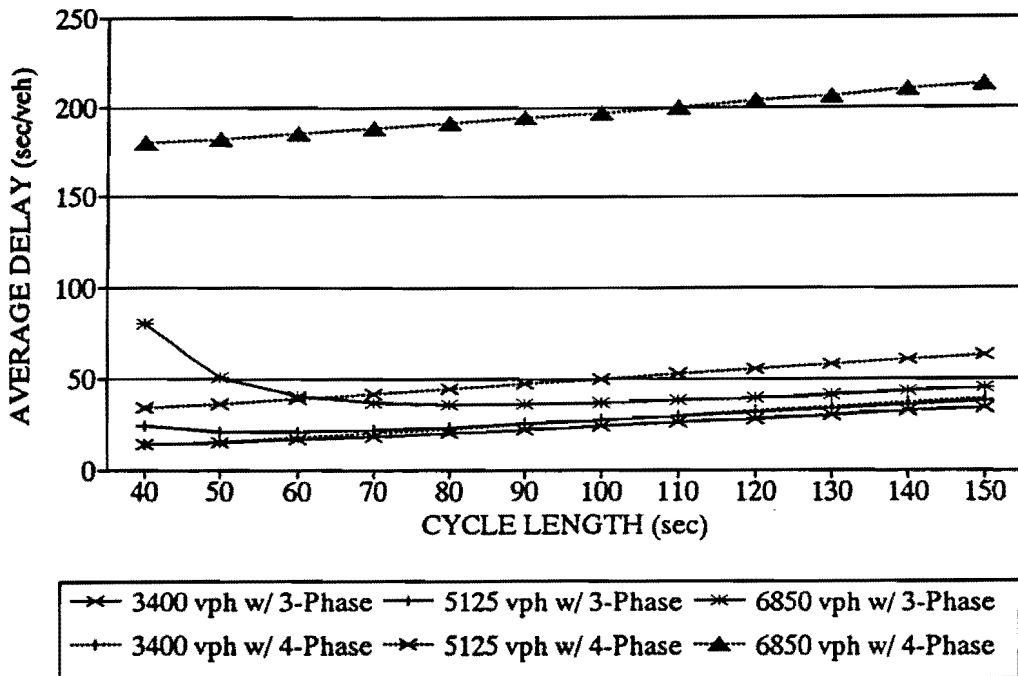


Figure 12. Case 2 Variation in Average Delay with Respect to Cycle Length.

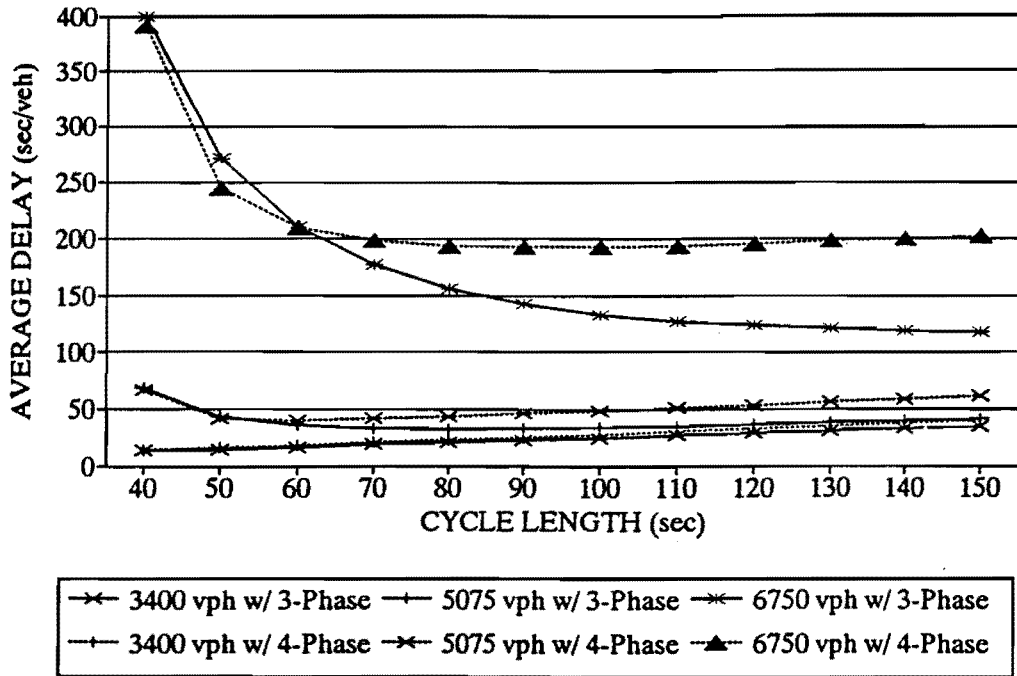


Figure 13. Case 3 Variation in Average Delay with Respect to Cycle Length.

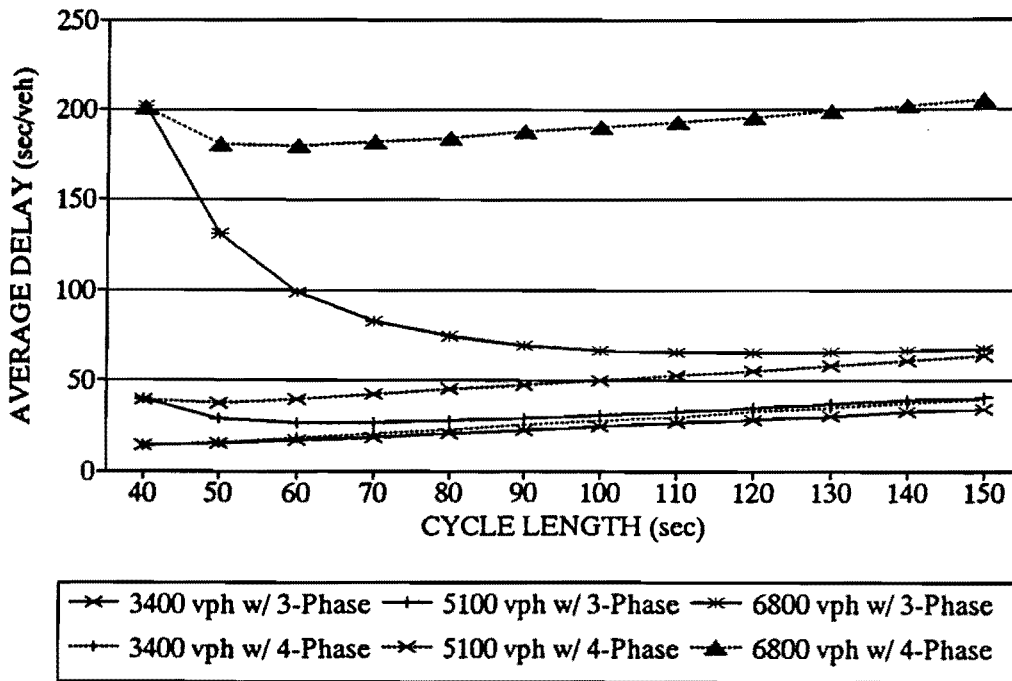


Figure 14. Case 4 Variation in Average Delay with Respect to Cycle Length.

Further study of the simulations reveal the following results. The Case 1 volume conditions shown in Figure 11 seemed to generate similar cycle lengths until the high volume condition was reached. During high volume conditions, the three-phase control strategy operated at a much lower cycle length than did the four-phase-with-overlaps control strategy. The Case 2 results presented in Figure 12 indicate that the four-phase-with-overlaps control strategy never reached an optimal cycle length for minimum average delay, while the three-phase control strategy achieved optimal cycle lengths between 50 and 80 seconds for higher volume conditions. Figure 13 shows the results of the Case 3 analysis. For this case the three-phase control strategy generally achieved a minimum average delay at cycle lengths approximately 10 seconds shorter than the four-phase-with-overlaps control strategy, which corresponds to the results found by Messer and Chang (26). Case 4 results, however, showed that the three-phase control strategy achieved a minimum average delay at cycle lengths much greater than the three-phase control strategy for high volume conditions. These results are shown in Figure 14.

The results obtained in this study were generally as expected, since three-phase operation offers the advantage of allowing left-turning movements on the frontage road approaches to move concurrently and store vehicles within the interior of the diamond interchange. These benefits of the three-phase control strategy were obtained at the expense of an increased number of stops per vehicle, since the three-phase control strategy normally does not allow for these movements to be progressed through the interchange. Therefore, since the three-phase control strategy in Case 1 and Case 3 offered only marginal improvements over the four-phase-with-overlaps strategy, the latter was probably a more appropriate strategy for implementation at certain exterior volume conditions due to the advantages offered by the progression of various movements.

The above results also indicate that the four-phase-with-overlaps control strategy does not handle symmetrical loading of the frontage road approaches very well in high volume conditions. The Case 1 results, where traffic volumes increased on only one side of the interchange, and Case 3 results, where traffic volumes increased only on the arterial

approaches, showed that both the three-phase and the four-phase-with-overlaps control strategies would operate reasonably well for these conditions. However, in Case 2, where traffic volumes increased only on the frontage road approaches, and Case 4, where traffic volumes increased on all approaches, the results indicated that four-phase-with-overlap control caused excessive delays. An explanation on this occurrence cannot be made based on the analyses performed and are beyond the scope of this report.

4.2 FORECASTING OPERATIONAL LIFE

Using the operational analyses previously performed, the performance characteristics were related to the traffic volume growth model developed as part of the growth trend analysis. The assumption was made that future traffic volumes would increase at a 3.2% annual growth rate equal to the historical trend over the most recent ten year period (2). A compounding growth equation (28) was used to relate increasing traffic volumes to time. The general form of the compounding growth equation is as follows:

$$F=P(1+r)^n \quad (1)$$

where:

- F = future traffic volume (vehicles);
- P = present traffic volume (vehicles);
- r = annual growth rate; and
- n = time period over which growth occurs (years).

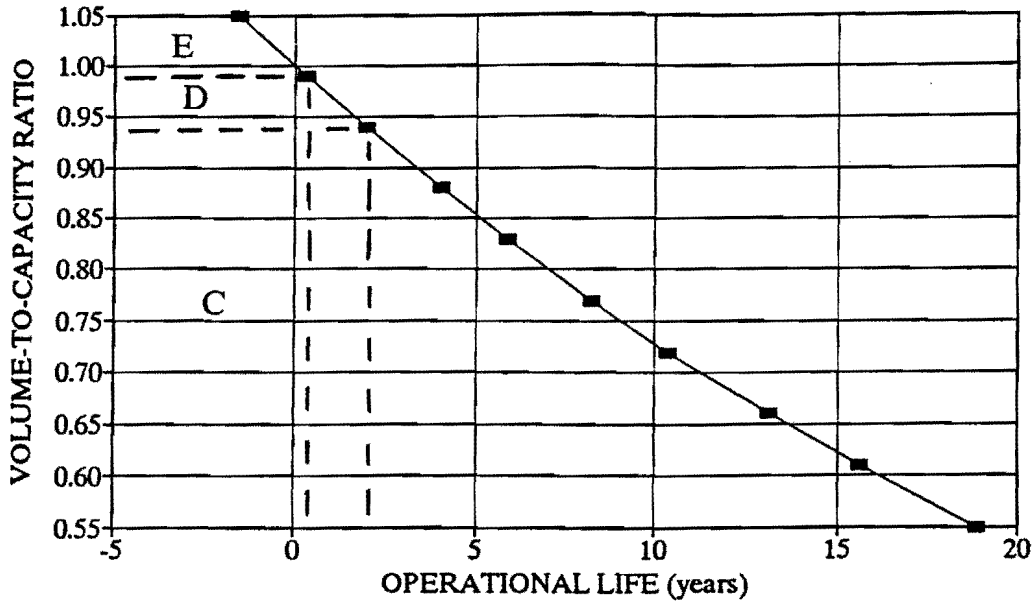
Based on the assumption that traffic volumes increase at a rate of 3.22 percent per year with all other factors remaining constant, the number of years required to reach the total exterior interchange approach volume was computed for each of the four cases studied. The time to reach a critical volume-to-capacity ratio of 1.0 was obtained by first computing the operational life from the base volume-to-capacity ratio to all other volume-to-capacity ratios. The time was then set equal to 0 for a volume-to-capacity ratio of 1.0 and the time to any other undersaturated critical volume-to-capacity ratio was then back-calculated. For the purposes of this study, critical volume-to-capacity ratio was defined as the highest lane

group volume-to-capacity ratio for the diamond interchange. Assuming that both the three-phase and the four-phase-with-overlaps control strategies operated at the same cycle length, an analysis was conducted to determine the remaining operational life of the interchange.

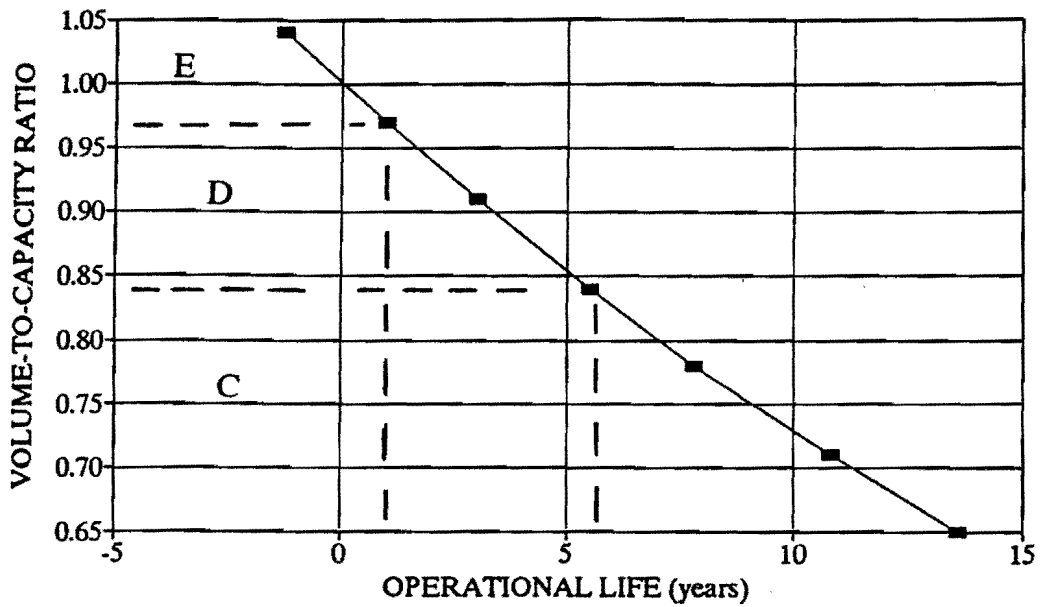
The analysis revealed that the remaining operational life was the same for each case using a particular control strategy. Since the operational life analysis was based a formulation using the volume-to-capacity ratio wherein the volume was considered to be the present value and the capacity was considered to be the future value, the results of the mathematical expression yielded identical results for like volume and capacity conditions. However, the level-of-service bandwidth associated with each operational strategy were quite different for the cases considered. The Case 4 results of this analysis are graphically represented in Figure 15 and the results for the other cases are given in Reference 2.

The results of the remaining operational life of the model urban diamond interchange showed that a three-phase control strategy may offer a more favorable level-of-service than a four-phase-with-overlaps control strategy for certain cases. These results were understandable, since a reduction in the total number of phases may greatly improve interchange operations. However, consideration must be given to interchange geometrics, accident patterns, and minimum delay cycle length in order to minimize the disadvantages of changing from a three-phase to a four-phase-with-overlaps control strategy.

Based on an interpretation of Figure 15, the traffic engineer could characterize the length of service afforded each level-of-service "C," "D," and "E" for both the three-phase and four-phase-with-overlaps control strategies. The Case 4 results indicated a service life for level-of-service "C" of over 17 years for three-phase control and over 8 years for four-phase-with-overlaps control. The service life for level-of-service "D" is approximately 2 years for three-phase control and 4 years for four-phase-with-overlaps control. The service life for level-of-service "E" is greater than 0.5 years for three-phase control and greater than 1 year for four-phase-with-overlaps control. The service life for level-of-service "E" varies depending on whether volume-to-capacity or delay is used as the measure of effectiveness.



(a) Case 3 Three-Phase



(b) Case 4 Four-Phase-with-Overlaps

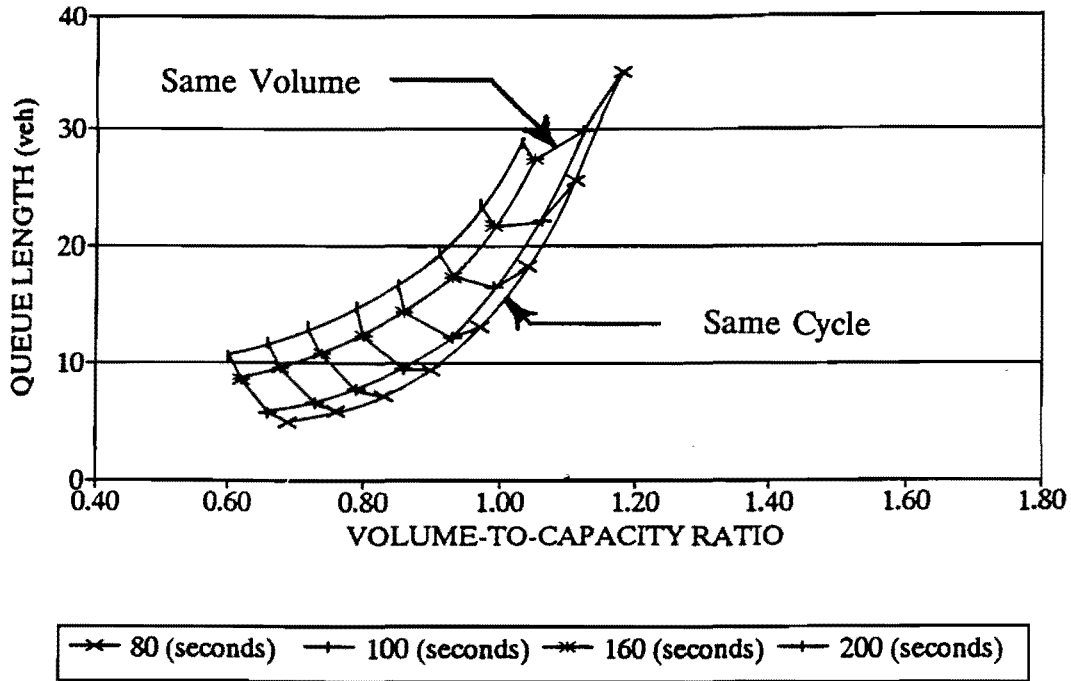
Figure 15. Operational Life of an Undersaturated Diamond Interchange Given the Present Volume-to-Capacity Ratio.

Approximate level-of-service regions are included in Figure 15, based on the operational analyses performed specifically for this study. It is noted that the Highway Capacity Manual (29) stated that volume-to-capacity has a very complex relationship with level-of-service. A poor choice of timing and phasing schemes or a lack of progression can greatly affect the volume-to-capacity ratio. It is also possible to have a level-of-service "F" at a volume-to-capacity of approximately 0.75 to 0.80. The use of the forecasting technique presented in this chapter requires site specific operational analyses to be performed in order to relate level-of-service to the critical volume-to-capacity ratio. However, such an analysis could provide insight into the need for future improvements.

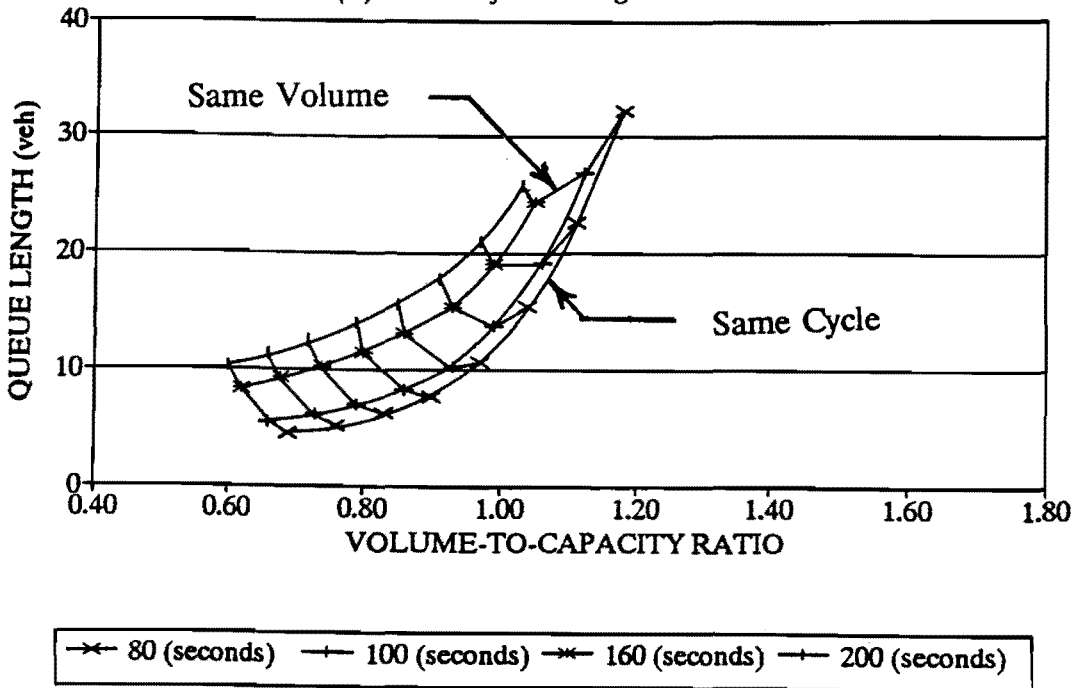
4.3 QUEUE DEVELOPMENT CHARACTERISTICS

In order to study queue development characteristics, a model was formulated and analyzed using the PASSER II-90 microcomputer program. PASSER II-90 was used in lieu of PASSER III-90 since the latter does not have the ability to determine queue development length. A simple intersection with four approaches and split phasing for each approach was operationally evaluated using the Case 4 traffic volumes, where all approach volumes were increased, to determine how cycle length affects queue development. PASSER II-90 was allowed to determine the optimal green splits for the four approaches while all other factors remained constant. Analyses were performed for all approach volume levels using cycle lengths of 80, 100, 160, and 200 seconds. The evaluation results for one approach are shown in Figure 16 and the other approach results are presented in Reference 2. The queue lengths shown represent the maximum number of vehicles stored per cycle per lane at the intersection for the various cycle lengths for given volume levels. Consideration was given only to the undersaturated operational region in this chapter and the oversaturated region is discussed in Chapter 6 on oversaturated analyses.

The simulation results revealed that a reduction in cycle length can reduce the length of the queue for volume-to-capacity ratios while in the undersaturated region. The results also showed that a 50 percent reduction in cycle length produces a similar reduction in



(a) NB Left-Turning Movements



(b) NB Through Movements

Figure 16. Queue Development versus Volume-to-Capacity Ratio for Sample Left-Turning and Through Movements.

queue development for undersaturated conditions. As the volume-to-capacity begins to transition to the oversaturated region, benefits of shorter cycle lengths are not as pronounced. The results also illustrated the fact that the volume-to-capacity ratio could vary as the timing and phasing schemes change for a specified total exterior traffic volume. Also illustrated was the fact that queue development for the left-turning movements occurs at a much greater rate than for the through movements; most likely as a result of operational penalties being assessed to the left-turning movements. Figure 16 also shows some trends are evident in the oversaturated region and these trends are discussed in Chapter 6 along with the oversaturated volume analyses.

In summary, it is important to recognize that Figure 16 shows plots of maximum queue lengths per cycle on a typical external approach for four different cycle lengths servicing a given volume level. Various volume levels were studied to produce a wide range of volume-to-capacity ratios (degrees of saturation). These results suggest that the lowest volume-to-capacity ratio does not always produce the shortest queue length. An interpretation of these results suggests that the cycle length tends to dominate signal control of the a queue management strategy in the undersaturated region, while the minimization of volume-to-capacity ratio tends to dominate in the oversaturated region. It also appears that there is a transition zone between these volume levels where some combination of these dominating factors should be considered. The oversaturated region will be considered in more detail in Chapter 6.

5.0 IDENTIFICATION OF ALTERNATIVE OVERSATURATED CONTROL STRATEGIES

This chapter reports on the findings of the national survey conducted of leading traffic engineering practitioners regarding congestion management and their knowledge of any alternative or innovative oversaturated diamond interchange traffic signal control strategies currently in use. The survey consisted of telephone interviews with 18 traffic engineers, traffic signal technicians, and traffic signal controller manufacturers working with major urban areas throughout the United States. A list of those individuals contacted together with their agency affiliations is given in the Appendix.

5.1 CONGESTION MANAGEMENT

The survey participants were arbitrarily selected from private, local and state organizations in order to maximize the diversity of opinions throughout the United States. Some of the participants discussed congestion management strategies that favored their jurisdiction. Local transportation officials indicated a need to manage queue development at urban diamond interchanges so that arterial street operational characteristics are improved; often at the expense of the operational efficiency of the frontage road approaches and ultimately the freeway or expressway facility. Meanwhile, some state highway officials chose an opposing viewpoint; one which enhances frontage road operations at the expense of the arterial street network. Job responsibilities of the survey participants may tend to bias some survey responses.

5.2 ALTERNATIVE OVERSATURATED DIAMOND INTERCHANGE CONTROL

The survey participants each were asked if they had knowledge of any oversaturated diamond interchange traffic signal control strategy other than traditional three-phase or four-phase-with-overlaps schemes. If so, they were asked to elaborate on the strategy. The

survey participants were also asked if they knew of any jurisdiction that may be considering an alternative or innovative strategy, so that the survey could be expanded.

The majority of the survey responses consisted of innovative techniques for using existing traffic signal control equipment to accomplish traditional three-phase and four-phase-with-overlaps control strategies. Such innovative techniques include the use of protective/permissive arterial street left-turn phasing, the use of individual interconnected traffic signal controllers which allowed either leading or lagging arterial street left-turn phases, and the use of eight overlaps rather than individual phases to accomplish a four-phase-with-overlaps phasing pattern. Other responses dealt with the ability to generate more efficient timing plans utilizing these techniques with traditional control strategies. The most innovative new diamond interchange control strategies were found in Texas.

One alternative oversaturated diamond interchange control strategy identified in the survey is currently being used by Mr. Bill Hensch, P.E. in and around the Houston metropolitan area. This strategy "double cycles" frontage road phases using the four-phase-with-overlaps phasing pattern. This strategy is currently operational in a fixed-time mode and is believed to be feasible using traffic actuated operation. The basis of this strategy lies in the redistribution of that time which would otherwise be wasted by an opposing frontage road phase while allowing for U-turning traffic. For instance, given a fixed time sequence on a frontage road approach where the approach traffic volume consists of predominately through movements. The traditional four-phase-with-overlaps strategy allows time for a U-turning movement. If the U-turning traffic volume is very low or nonexistent then the time normally wasted by the overlap phase at the downstream intersection is reallocated to the opposing frontage road phase. This allows the opposing frontage road phase to run during this time and during the time allowed for its normal sequence, thus "double cycling." This operational strategy is also known as "conditional service."

Field observations suggest that the conditional service operational strategy seems to work best when the frontage road approach traffic stream consists of mainly through

movements. It should be noted that this strategy does not allow for the progression of left-turning traffic from the donorside frontage road approach since the opposing frontage road phase is running concurrently. If appreciable left-turning volumes exist for this movement, interior queueing would occur, resulting in poor interchange operation. The strategy also favors locations where the interchange is not complete and all of the main lane through traffic is using the frontage roads. The strategy also works very well when turnarounds are present at the interchange.

Another innovative strategy for improving operations at oversaturated signalized diamond interchanges is currently being used by Mr. Harvey Beierle of TxDOT in the San Antonio District. This strategy involves the use of the Time-to-Reduce feature available in existing diamond interchange signal control equipment to prevent a phase from extending when vehicles are only occupying a single lane of a multilane approach. In this strategy the Time-to-Reduce feature reduces the available extension time to a point where it will be less than the actual vehicle headway if vehicles occupy only a single lane. When vehicles occupy more than one lane, the detector activations will occur at shorter intervals than the actual vehicle extension headway and the phase would continue to be extended. This strategy could be used to improve the operational efficiency of a signalized diamond interchange by placing more emphasis on approaches which are entirely saturated, rather than on approaches where single lane queueing occurs. The strategy is currently being used in the San Antonio urban area using traditional multiloop detection systems without any apparent sacrifices in safety. Field observations of this strategy by local district traffic personnel indicate that the approach works well and seems to improve the overall efficiency of the interchange.

6.0 EVALUATION OF ALTERNATIVE OVERSATURATED CONTROL STRATEGIES

The evaluation of alternative oversaturated diamond interchange control strategies is explored in this chapter. Kim and Messer (9) successfully demonstrated that optimal oversaturated diamond interchange signal timing plans could be generated to maximize system productivity, minimize system delay, and manage queue backups. This research task was an effort to build upon this previous research and explore presently practical methodologies to manage queue development at an oversaturated urban diamond interchange. Consideration was first given to a study of the queue development characteristics of an oversaturated diamond interchange. A comparison of control strategies was performed next. Finally, a strategy for queue management at oversaturated traffic actuated diamond interchanges was developed.

6.1 QUEUE DEVELOPMENT CHARACTERISTICS

This evaluation begins by looking back at the problem formulated to study queue development in the study of undersaturated operations and focusing on the region with a volume-to-capacity ratio greater than 0.8 in Figure 16. Volume-to-capacity ratios from 0.8 to 1.2 represent the region where operations are moving from undersaturated to oversaturated. Considering a change in cycle length for given traffic volume levels, the figure shows the queue development and volume-to-capacity ratio as a function of the cycle length (more specifically, the green split for this one approach) as oversaturation is approached. The figure indicates that there may exist some optimal green split where queue development and the volume-to-capacity ratio are minimized. The Kim and Messer approach to oversaturated diamond interchange control used a similar hypothesis as a foundation for computing optimal timing plans which increase system productivity and manage the formation of approach queues. This previous research indicated that queue development could be managed on oversaturated diamond interchange approaches using a dynamic pretimed method of operation.

6.2 COMPARISON OF CONTROL STRATEGIES

The results of the national survey did not provide any new or innovative oversaturated diamond interchange control strategies. Therefore, this section reports on a comparison of oversaturated urban diamond interchange operational characteristics using only traditional undersaturated diamond interchange control strategies. The traditional undersaturated three-phase and four-phase-with-overlaps control strategies were analyzed for the highest volume conditions in each of the four cases outlined in the experimental design.

The TEXAS Model was used to simulate traffic actuated control using the default detector arrangements for each control strategy. A maximum cycle length of approximately 90 seconds was arbitrarily selected for these analyses in an attempt to utilize the shortest practical cycle length which could be realistically implemented in oversaturated conditions at an urban diamond interchange. A minimum green time of 10 seconds was selected, along with a yellow time and red clearance of 3 seconds and 1 second, respectively. For reporting purposes, each of the four cases were replicated five times and the operational measures of effectiveness then pooled to reduce the effect of stochastic variation and eliminate any outlier results.

The results of the oversaturated diamond interchange analysis are shown in Table 2 and shown graphically in the following figures. Figure 17 shows that approximately the same number of vehicles were processed for each of the four cases except Case 3, where the three-phase control strategy processed approximately 100 vehicles more than the four-phase-with-overlaps control strategy. This occurrence was interpreted as having been the result of a variation in actuated phasing for two of the five replications which favored the traffic volume increase only on the arterial approaches. When using three-phase traffic actuated signal control at a diamond interchange, two combinations of left-turning and through movements on the arterial approaches can occur. One combination allows the left-turning and the through movement on the arterial approaches to move concurrently. Another

Table 2. Oversaturated Operational Characteristics

Case	Total Vehicles Processed (veh)	Overall Average Delay (sec)	Overall Average Queue Delay (sec)	Maximum Queue (veh)
Three-Phase				
1	801	121.6	165.3	33
2	957	118.9	143.1	35
3	940	87.8	124.5	32
4	943	72.7	112.9	32
Four-Phase with Overlaps				
1	804	117.1	160.5	32
2	952	137.0	194.2	32
3	863	95.7	135.4	32
4	948	91.4	136.5	30

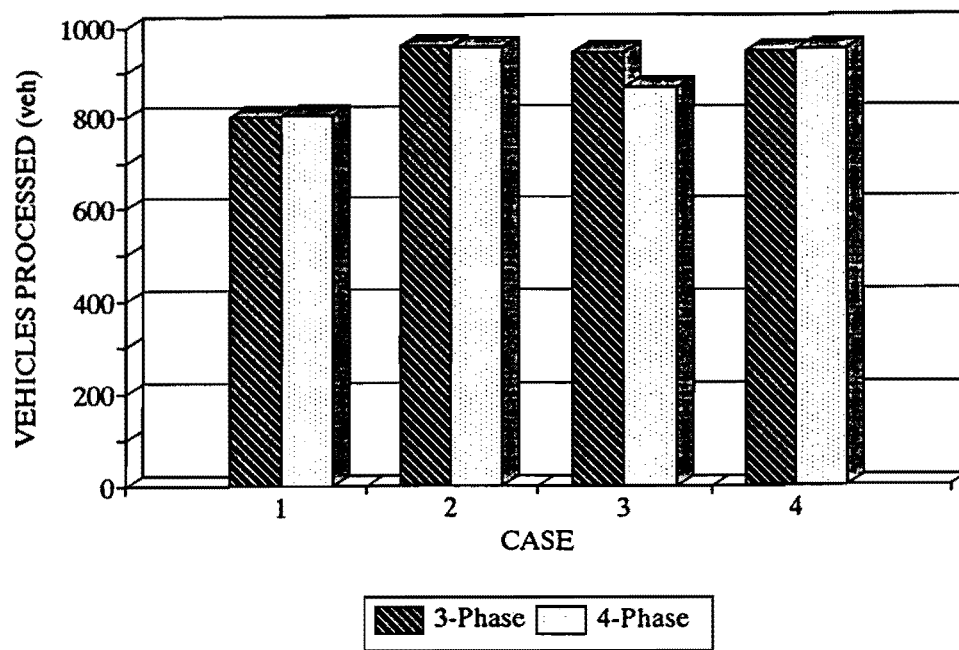


Figure 17. Comparison of Vehicles Processed for an Oversaturated Urban Diamond Interchange.

combination allows both through movements on the arterial approaches to move concurrently, followed by a left-turn clearance phase. In the two replications cited, the arterial street through movements moved concurrently, whereas, they operated separately for the other three replications. The variation appears to be the result of a variation in the stochastic arrival rate of approach traffic for each of the arterial street movements.

Figure 18 shows the average stopped delay for the two control strategies compared for each of the four cases of increasing traffic volumes. The results showed that for Case 1, where traffic volumes increased only on one side of the interchange, the four-phase-with-overlaps control strategy produced less average stopped delay than the three-phase control strategy. Traffic conditions in this case favored the use of the four-phase-with-overlaps control strategy through benefits derived using the overlap times in connection with relatively short phase durations on the side of the interchange without increasing traffic volumes. However, the magnitude of the values was so small that no clear recommendation could be made for either control strategy. Case 2, where traffic volumes increased only on the frontage roads, results showed clearly that three-phase control should be favored. The three-phase control strategy allows the frontage road approaches to move in different phases, results in a more efficient utilization of the available green time, and has a fewer number of total phases than the four-phase-with-overlaps control strategy. Case 3, where traffic volumes increased only on the arterial approaches, results tended to favor the three-phase control strategy. Again, there was not a great difference in the average stopped delay between the two strategies. Case 4, where traffic increased on all approaches, results favored the three-phase control strategy. The difference in average stopped delay in this case was believed to be the result of the three-phase control strategy operating at a shorter overall cycle length than the four-phase-with-overlaps with basically the same amount of green time available to each approach.

Figure 19 shows the average queue delay for the two control strategies compared for each of the four cases of increasing traffic volumes. The results showed that for Case 1 the four-phase-with-overlaps control strategy produced less average queue delay than the three-

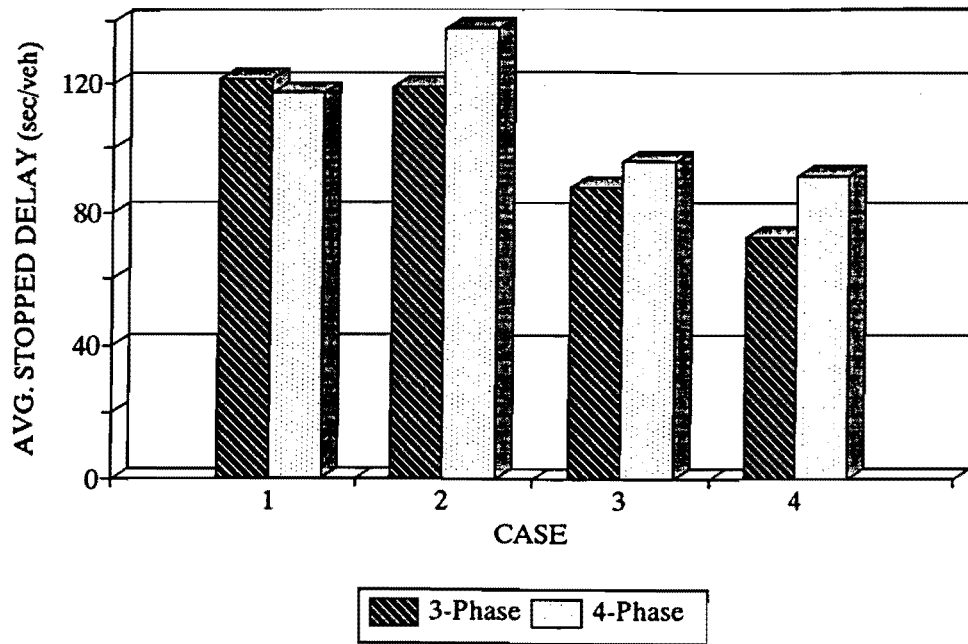


Figure 18. Comparison of Average Stopped Delay for an Oversaturated Urban Diamond Interchange.

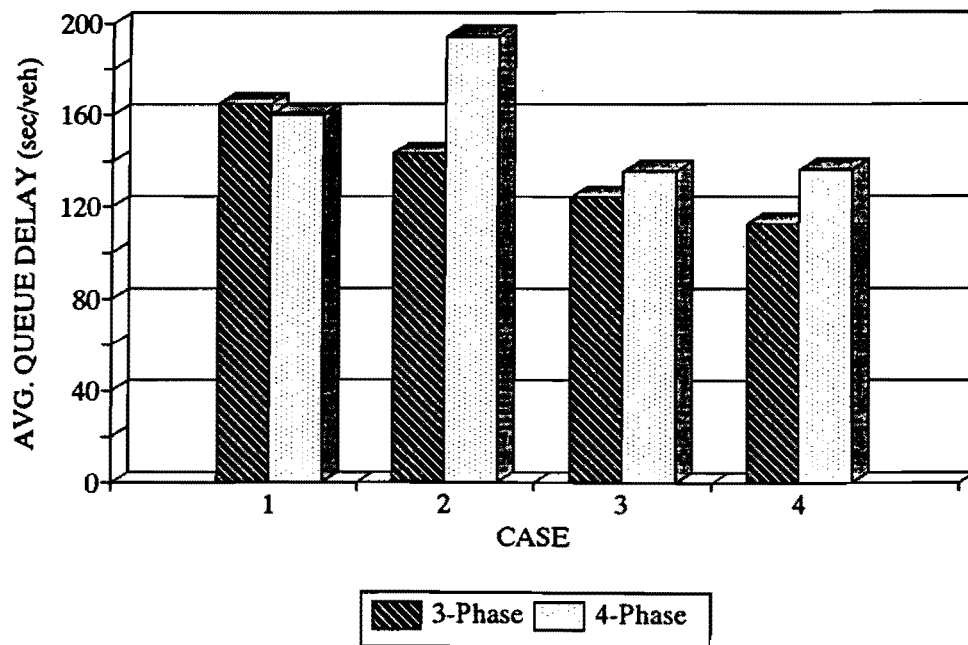


Figure 19. Comparison of Average Queue Delay for an Oversaturated Urban Diamond Interchange.

phase control strategy. Again, the magnitude of the values was so small that no clear difference could be seen between either control strategy. The Case 2 analysis clearly showed that three-phase control should be favored. The fewer number of phase allows each approach to be serviced quicker, resulting in less queue delay. Again, the Case 3 scenario again tended to favor the three-phase control strategy, but the difference in queue delay between the control strategies was minimal. Case 4 favored the three-phase control strategy. The difference in average queue delay in this case was again believed to be the result of the three-phase control strategy operating at a shorter overall cycle length than the four-phase-with-overlaps with basically the same amount of green time available to each approach.

Figure 20 shows the maximum queue development for each of the four cases of increasing traffic volumes. The results of this analysis indicated that for Case 1 and Case 3 there was no real difference in the maximum queue developed between the two control strategies. However, the Case 2 and Case 4 results indicated that the maximum queue developed for the three-phase control strategy was greater than that of the four-phase-with-overlaps control strategy. In the latter two cases, the average number of vehicles processed were virtually identical and both the average stopped delay and average queue delay favored the three-phase control strategy; yet the maximum queue development with three-phase was greater than with the four-phase-with overlaps control strategy. This level of analysis does not indicate a reason for this occurrence, however, it is believed that these results may be due to the four-phase-with-overlaps control strategy operating closer to an optimal queue management cycle length than the three-phase control strategy.

The results reported in this section generally followed expected trends, based on a review of the literature on diamond interchange control. Three-phase diamond interchange control offered the advantage of having fewer phases, resulting in more available green time, for a given cycle length, over four-phase-with-overlaps control. In the case where traffic volume increased only on one side of the interchange, the four-phase-with-overlaps control strategy offered the advantage of an additional amount frontage road green time equal to the offset time.

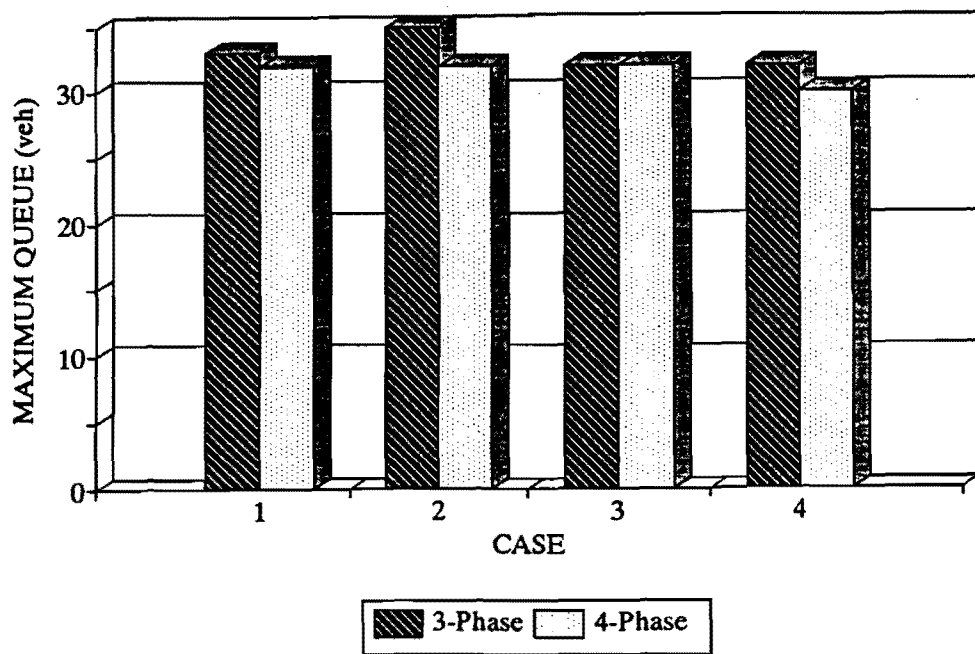


Figure 20. Comparison of Maximum Queue for an Oversaturated Urban Diamond Interchange.

6.3 TRAFFIC ACTUATED QUEUE MANAGEMENT STRATEGY

Previous research had indicated that queue development could be managed for oversaturated diamond interchanges operating on a fixed-time basis. This research task focused on the development of a queue management strategy for traffic actuated oversaturated diamond interchanges. The strategy was developed using only Case 4, where traffic volumes increased on all approaches, for oversaturated conditions, as previously outlined in the experimental design section.

The queue management strategy for traffic actuated diamond interchanges consisted primarily of a redistribution of available green time to favor the approach selected for a reduction of queue development. This strategy was based on the hypothesis that a minimal reduction of phase green time for all other approaches would not dramatically impact their operation, while the addition of this time to the subject approach will reduce queue development. To test this strategy, the previously described Case 4, with four-phase-with-overlaps control, was again analyzed to obtain measures of effectiveness which were compared to the original Case 4 oversaturated analysis. The TEXAS Model was again used to evaluate the performance of the strategies.

Phase 7, as shown in Figure 6, was arbitrarily chosen as the subject phase for queue reduction. The design of this experiment consisted of maintaining a 90 second maximum cycle length and varying the external maximum phase durations by five seconds and adding this time to the target phase, Phase 7. The objective of this experiment was to reduce the queue development on Phase 7 while not adversely impacting the overall measures of effectiveness of the urban diamond interchange. The TEXAS Model was used to evaluate the strategy and obtain the measures of effectiveness.

The implementation of this strategy proved to be successful. By reducing the external phases by 5 seconds each (20 percent each) and adding this time to Phase 7 (an increase of 60 percent) the queue was reduced by approximately 30 percent without dramatically

affecting the other approaches. The results shown in Table 3 and Figures 21 - 24 indicated queue development could indeed be reduced, while the maximum queue developed for the total interchange remained unchanged. Figure 21 shows a queue reduction of seven vehicles per lane, which equates to approximately 175 feet. The maximum queue development for the overall diamond interchange remained constant, as shown in Figure 22. Figure 23 indicates that there was an increase in the total number of vehicles processed in the system. The average queue delay, shown in Figure 24, and the average stopped delay, shown in Figure 25, both increased slightly, probably due in part to the use of suboptimal green splits for the system with the queue management strategy.

Table 3. Oversaturated Operational Characteristics Using the Proposed Queue Management Strategy

Case	Total Vehicles Processed (veh)	Overall Average Stopped Delay (sec)	Overall Average Queue Delay (sec)	Maximum Average Approach Queue (veh)	Phase 7 Average Approach Queue (veh)
4	804	117.1	160.5	32	24
4(alt)	961	143.6	172.6	32	17
Variation	157	26.5	12.1	0	-7

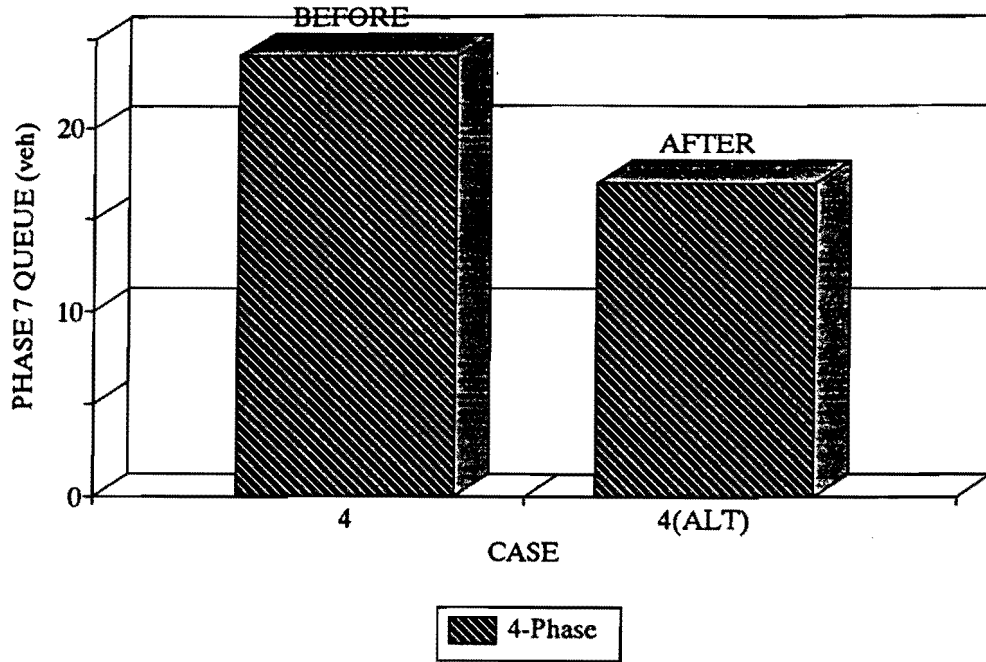


Figure 21. Queue Management Strategy Queue Reduction of Maximum Queue per Cycle per Lane.

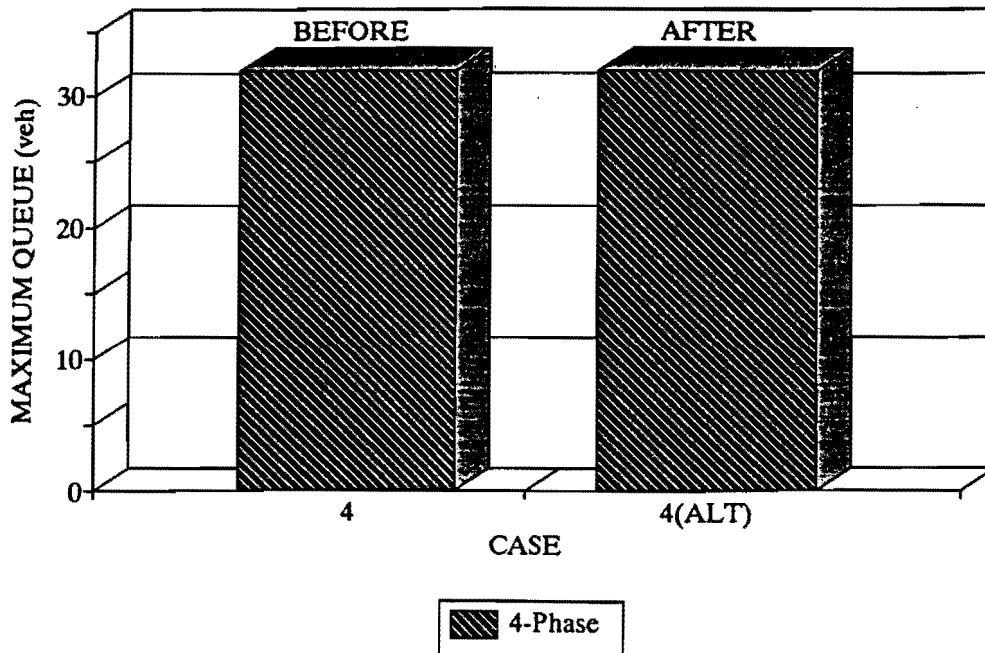


Figure 22. Queue Management Strategy Maximum Queue per Cycle.



Figure 23. Queue Management Strategy Vehicles Processed.

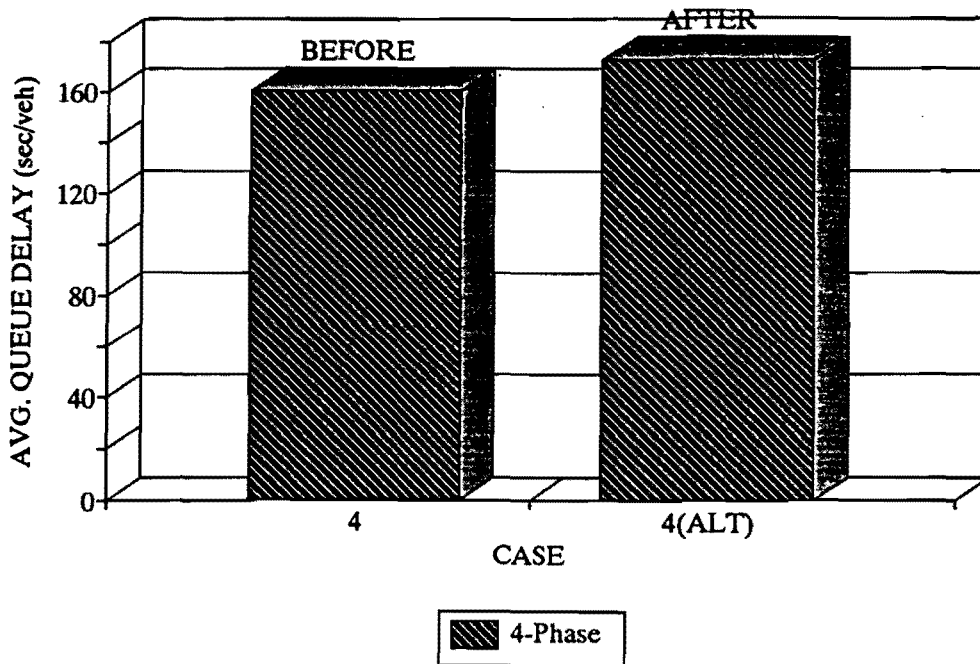


Figure 24. Queue Management Strategy Average Queue Delay.

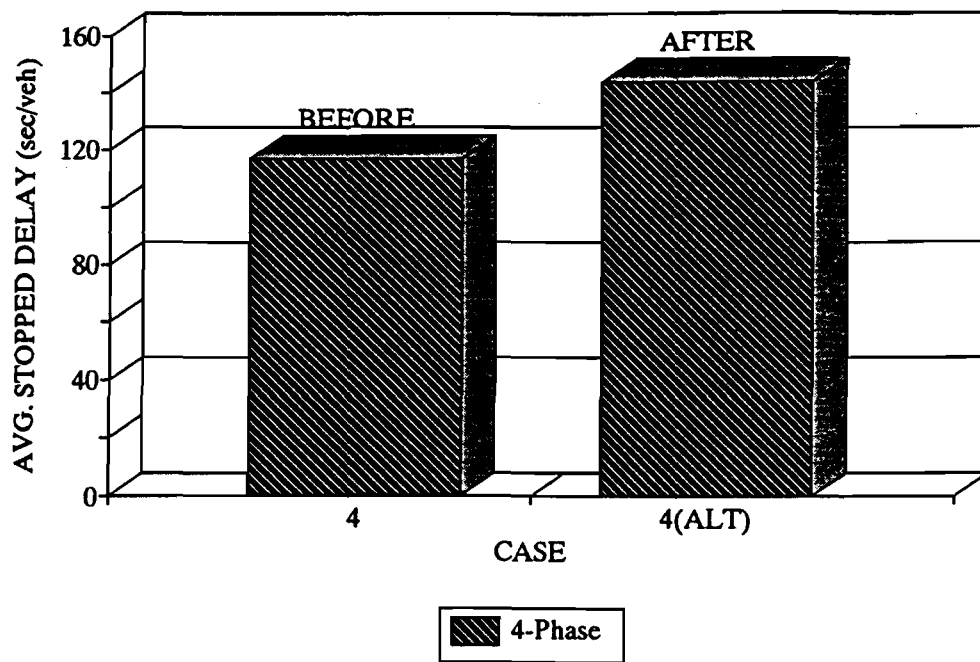


Figure 25. Queue Management Strategy Average Stopped Delay.

6.3.1 Field Implementation of the Table 3 Queue Management Strategy

This section describes the system requirements for implementing the queue management strategy, described previously in Table 3, in the field using current technology. Since standard diamond interchange control systems usually do not provide features for readily implementing a responsive queue management strategy on demand in real time, some recommended features for future control systems are also provided.

The Table 3 queue management strategy, described earlier in this report, could be implemented in a field situation using existing control equipment without too many modifications. First, the traffic engineer needs a thorough knowledge of the geometrics, traffic patterns, and operating characteristics of the subject diamond interchange. Of major importance is the identification of when the interchange becomes oversaturated, the movements that become oversaturated, and the length of time the interchange remains oversaturated. This information is then used by the traffic engineer to generate oversaturated signal timing plans.

Second, an optimal control objective should be identified in the oversaturated region, the control objective should take the form of queue management. The maximum allowed queue development length on all approaches should be determined. This should include a study to determine the impacts of queue development into adjacent freeway mainlanes, closely spaced signalized intersections, locations where safety issues might arise, and into high volume traffic generators in the area.

Third, a means of identifying the point in time to implement the queue management strategy is required. After determining the maximum queue development length, a point of implementation for the oversaturated control strategy should be derived. This point should be less than the maximum allowable queue development length to permit additional queue development during the transition period, probably 75 percent of the maximum queue development distance. The provision of queue detection on the external approaches at the "queue detection points" would provide a means of calling for the implementation of the

oversaturated control strategy, as in the Arlington system, and for a more extreme control strategy, if necessary, at the "critical queue detection points." Figure 26 shows a typical urban diamond interchange which has the recommended queue detection concepts identified for one approach to the interchange. Various types of detector technology might be utilized to achieve the desired detection functions.

Fourth, the traffic engineer should perform an operational analysis of the interchange to determine the optimal timing plan for the interchange which will manage the queue development lengths. This can be accomplished either through the use of the Kim and Messer approach or through an extensive analysis of optimal timing plans using PASSER II-90, PASSER III-90, and the TEXAS Model.

Finally, the system can be implemented in such a manner so as to allow the detection system, after occupation for a certain duration, to signal a need for the implementation of queue management and for the control system to initiate a predetermined timing plan which maintains a constant optimal cycle length. Street approaches which are not utilizing the entire newly implemented oversaturated maximum green period can remain traffic responsive, provided that the cycle implemented for the entire congestion period operate at the predetermined duration. The implementation of this strategy should be for a minimum of 15 to 30 minutes since some time will be required for transition and stabilization. It is believed that through the use of this strategy and existing traffic signal control equipment that efficient operations can be maintained during oversaturated periods at diamond interchanges.

6.4 FUTURE CONTROL EQUIPMENT CAPABILITIES

As noted previously in this report, diamond interchange signal control equipment has evolved from pretimed to traffic actuated. Control, equipment is currently available with the capability of switching from a three-phase control strategy to a four-phase or four-phase-with-overlaps control strategy. Existing equipment can also be used to detect the

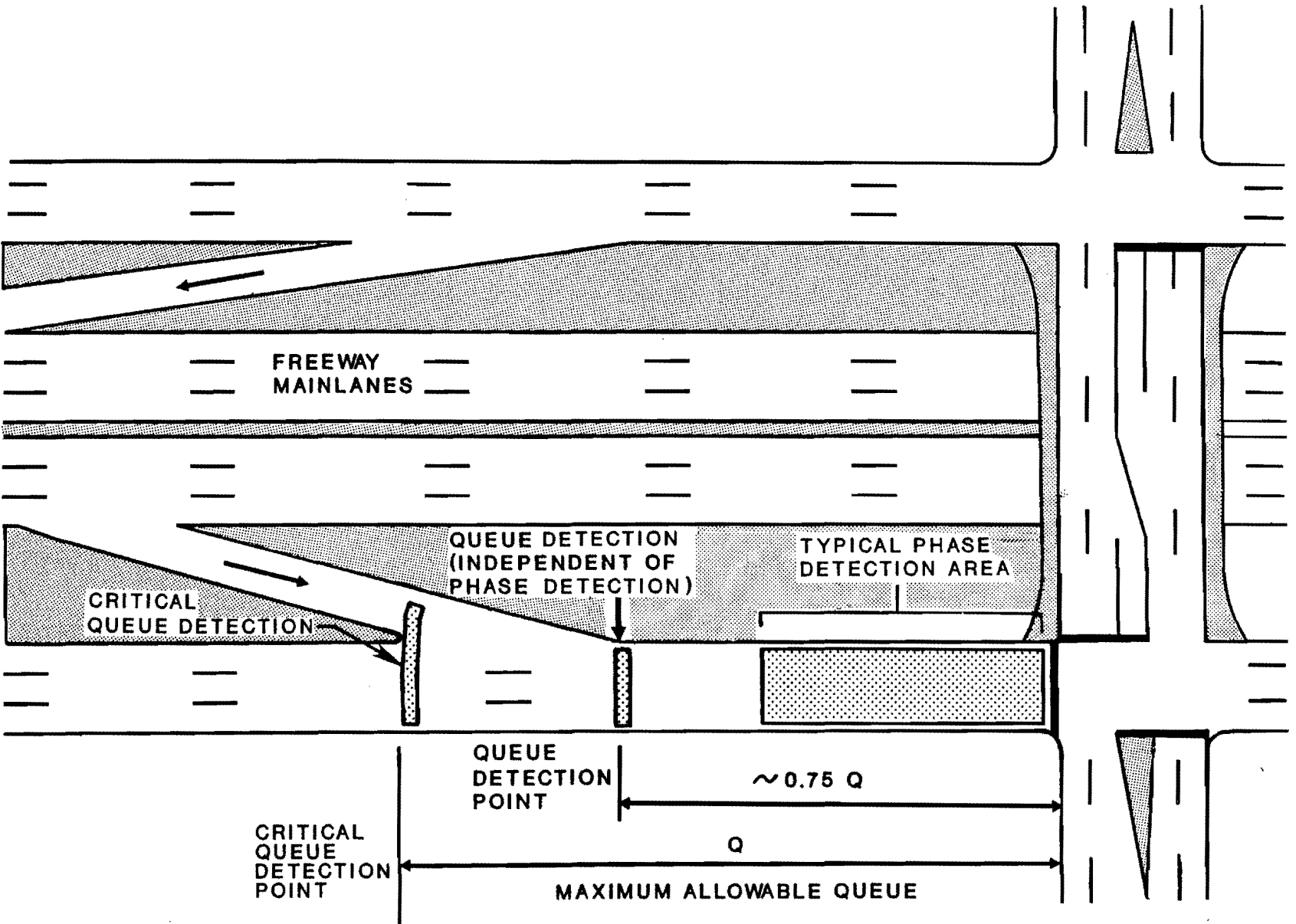


Figure 26. Proposed Oversaturated Control Strategy for Queue Management on a Single Approach.

presence of single lane queueing and place greater emphasis on other more saturated approaches. However, there exists a need to look to the future to identify the functional capabilities of future diamond interchange control equipment so that it can efficiently serve a wider range of traffic conditions, including those interchanges experiencing recurrent and non-recurrent congestion due to oversaturation. Enhanced control systems will be desired by the profession that provide advanced detection and control strategies.

The features of future "smart" diamond interchange signal control systems should provide operational capabilities for both the undersaturated region and the oversaturated regions of operation, as well as the volatile transition zone between them. Existing traffic actuated signal control features serves the undersaturated region very well.

Additional control capabilities are needed to operate in the oversaturated region. Some enhanced functions for diamond interchange control equipment that would provide for the implementation of oversaturated control strategies are identified in Tables 4 and 5. New functions are needed to allow for reducing the phase duration when conditions become congested, much as the phase extension time increases the available green time in undersaturated operations. A means by which an optimal queue management cycle length can be internally computed based on prevailing conditions should also exist for the oversaturated region of operations. A need exists to implement optimal queue management strategies in a timely manner, particularly when operations are in a state of transition from the undersaturated region to the oversaturated region. Appropriate indicators are required on the exterior of the control unit to readily identify the current region of operation, status, and other various parameters including the number of max-outs and gap-outs by phase occurring over a specified time frame. Finally, the diamond interchange signal control equipment of the future needs to be more intelligent than existing equipment. In summary, smart diamond controllers need to be able to detect and identify the prevailing operating conditions, determine the optimal control strategy, and respond in a timely manner. Should the controller determine that this protocol cannot be followed, then it should report the situation to higher system authority.

Table 4. Timing Parameters For New Diamond Controller Unit

Existing Parameters	Proposed Parameters
Minimum Green (sec) Extension (sec) Initial Gap (sec) Minimum Gap (sec) Time Before Gap Reduction (sec) Time to Reduce Gap (sec) Walk (sec) Ped Clearance (sec) Maximum Green I (sec) Maximum Green II (sec) Yellow Clearance (sec) Red Clearance (sec) Red Revert (sec)	All Existing Parameters <u>Plus The Following</u> Oversaturated Maximum Green (sec) Minimum Oversaturated Duration (min) Cycles to Reduce Max Green (each)

Table 5. Detector Functions For New Diamond Controller Unit

Type	Function
Phase	Call and Extend Phase. Determine if single lane queueing is occurring so that other approaches with greater demands may be serviced.
Queue	Call Predetermined Phase Duration for oversaturated condition. Forces all phases to an oversaturated pattern.

These are only a few of the current needs for diamond interchange signal control equipment as the transition is made from second generation to third generation traffic signal control equipment. It may be some time before the evolution of traffic signal control equipment from second generation to third generation is complete. To be sure, there are many unknowns that research will need to address before full development and optimal implementation can occur. Additional research needs to be conducted on many aspects of queue management, including the provision of an optimal cycle length based on queues.

Finally, Intelligent Vehicle Highway System (IVHS) technology is rapidly approaching on the horizon whereby real time traffic identification and travel demand management should be possible. Moreover, telecommunications to and from the controller unit should become routine. Communications will not only be to master and secondary controllers, and to traffic engineering supervisory staff, but also to motor vehicles in the control area and to other control modes, such as freeway ramp metering systems and transit operations.

7.0 CONCLUSIONS AND RECOMMENDATIONS

This final report addressed primarily one important traffic control objective. This objective consisted of the identification of alternative signal control strategies to help alleviate congestion during high-volume, oversaturated diamond interchange operational conditions. This objective was achieved through a review of historic urban freeway traffic volume data, an operational analysis of various undersaturated control strategies for a typical urban diamond interchange, a national survey of traffic engineering practitioners, and an analysis of various oversaturated control strategies using a wide variety of complex microscopic and macroscopic computer simulation models of traffic operations.

The remainder of this chapter summarizes the findings from this research. Conclusions formulated from the research results are also described. Finally, recommendations are presented as a result of this research.

7.1 FINDINGS

An examination of historic traffic volume characteristics by Herrick (2) revealed that traffic demand in Texas urban areas is increasing at a rate of approximately 3.2 percent per year. This increase is based on an aggregation of the six major urban areas in the state. Individual urban areas often experience dramatic fluctuations in traffic demand based on social and economic conditions within each area. However, if it is assumed that traffic demand will continue to increase based on this historic trend, forecasts of future traffic demand is possible through extrapolation of this historic trend data.

Assuming traffic demand will continue to grow at the rate indicated by the historic trend, the length of time remaining before a diamond interchange becomes oversaturated can be forecasted. Using the critical volume-to-capacity ratio for the interchange, the operational service life for traditional three-phase and four-phase-with-overlaps control can be predicted. Service life based on volume-to-capacity is identical for the three-phase

control strategy and the four-phase-with-overlaps control strategy. However, the level-of-service bandwidth is site specific and varies considerably between the strategies. When considering service life it is important to compare equitable operational strategies, otherwise the analysis may favor one strategy over the other.

Three-phase control offered marginally improved diamond interchange operations over four-phase-with-overlaps control for identical cycle lengths for two of the four undersaturated cases studied. Additionally, three-phase control provided significant improvements for the case where traffic volumes on the cross street increased while volumes on the frontage road approaches remained unchanged. These findings are as expected since a reduction in the number of phases allows more green time for a given cycle length. The major operational problem with three-phase control during high-volume conditions remains the problem of potential internal gridlock (26, 27).

The national survey of traffic engineering practitioners indicated that no alternative oversaturated diamond interchange control strategy is currently in use. However, there were indications of innovative techniques for using existing traffic signal control equipment to accomplish traditional control strategies. Most of the research work with diamond interchanges was found to have been conducted within the state of Texas. This is most likely a result of the extensive use of continuous frontage roads within the state, particularly within the urban areas, and the need to achieve maximum efficiency of these facilities.

The oversaturated diamond interchange analysis focused on the use of traditional undersaturated diamond interchange control strategies. An analysis revealed that a traditional three-phase strategy should be favored for high-volume conditions given that internal gridlock can be avoided. Given this caveat, the next most important factor to consider in the case of oversaturated diamond interchanges is the management of the queues forming on the various external approaches. Agency interests may be competing in the development of queue management strategies. Local transportation officials may stress the need to reduce queueing on the arterial cross street in order to enhance progression,

thereby, providing greater operational efficiency for the arterial network at the expense of the freeway or expressway facility. Meanwhile, state highway officials may suggest a strategy of managing queue lengths such that vehicles do not back onto the mainlane freeway or expressway facilities and impede their operations, possibly at the expense of the arterial street network. This research also found that through the redistribution of available green time, queue development could be reduced on a specific oversaturated diamond interchange approach without dramatically affecting the queue development of the other approaches.

7.2 CONCLUSIONS

Based on the results of this research, the following conclusions are drawn from the data reviewed and the analyses performed within this study. These conclusions are based on the operational analyses performed on projected traffic volumes using these trends, assuming no other changes to the diamond interchange operating environment.

1. It is possible to determine the remaining operational service life for a particular urban diamond interchange using the procedure outlined in the chapter on undersaturated analyses, assuming no other changes in the operating environment. In order to determine the available service life for a signalized diamond interchange, operational strategies must be compared on an equitable basis. Advantages may be derived from changing interchange control strategies if the level-of-service bandwidth is more favorable for that strategy.
2. Cooperation between both state and local transportation agencies and officials is essential to provide both long-range and short-range strategies for effective traffic operations along major urban freeways.
3. While in a state of transition from undersaturated operations to oversaturated operations, queueing often becomes a problem on urban diamond interchange approaches. The problem then becomes worse if the interchange remains

oversaturated for a period of time. This report determined that there exists an optimal green split, and ultimately an optimal cycle length, which minimizes queue development for a given volume level.

4. In oversaturated diamond interchange operational conditions, the management of queue is of primary concern. External queue development can be controlled through the redistribution of available green time without greatly impacting the other interchange's approaches.
5. The selection of operational control strategies should be based on operational measures of effectiveness for urban diamond interchanges.

7.3 RECOMMENDATIONS

This report has provided insight into the statewide urban area traffic growth trends and performance characteristics of both undersaturated and oversaturated diamond interchanges. A number of recommendations are presented as a result of this research.

1. It is recommended that additional research be conducted relative to oversaturated diamond interchange control. A better understanding of how to effectively manage queue development on all interchange approaches is needed. Additional work is also needed to further investigate the existence of a minimum queue cycle length.
2. Manipulations of traditional control strategies can be used effectively to postpone oversaturation; however, queue management must be considered ultimately to prevent the consequences of oversaturation at diamond interchanges from adversely affecting mainlane operations. Table 6 provides recommendations for the selection of operational control strategies based on the urban diamond interchange analyzed in this report. Traditional control strategies are recommended for undersaturated

Table 6. Recommended Urban Diamond Interchange Control Strategies

V/C	Region	Control Strategy
0.5 0.6 0.7	U N D E R S A T U	Utilize either 3-phase or 4-phase-with-overlaps control strategy using optimal green splits with the control objectives of minimizing stops and delays. Traffic actuated control or well timed multi-dial fixed-time control can be used effectively. Keep the cycle length reasonably short and traffic moving.
0.8 0.9	R A T E D	Utilize either 3-phase or 4-phase-with-overlaps control strategy using optimal green splits with the control objectives of minimizing stops and delays on uncongested approaches and minimizing queue development on congested approaches. Traffic actuated control can be used and serious consideration should be given to controlling the cycle length for maximum effectiveness.
1.0 1.1	O V E R	Utilize either 3-phase or 4-phase-with-overlaps control strategy using optimal green splits with the control objectives of minimizing queue development on congested approaches and minimizing stops and delays on uncongested approaches. Control strategies should focus on controlling the cycle length with green extension.
1.2 1.3 1.4 1.5	S A T U R A T E D	Utilize either 3-phase or 4-phase-with-overlaps control strategy using optimal green splits with the control objective of minimizing queue development on critical approaches. Consideration should be given to using the traffic detection functions shown in Figure 26.

operations and new control strategies using the detector strategies of Figure 26 which focus on queue management are recommended for oversaturated operations.

3. Consideration should be given to the practical implementation of congestion management strategies. Officials should take a realistic approach to traffic projections and the consequences forecasted; and consider what the transportation system is truly capable of handling. The implementation of traffic demand management techniques are also recommended as oversaturated conditions become apparent.
4. Finally, the traffic engineering and traffic signal control manufacturing industry should provide signal control equipment which can handle both undersaturated and oversaturated operational conditions since it is presently needed in many urban areas. Efforts should be made to prepare specifications and manufacture equipment to effectively handle this need.

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