Technical Report Documentation Page

1. Report No. FHWA/TX-94/1297-2F	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle EVALUATION OF FLASHING TRAFFIC SIGNAL OPERATION		5. Report Date November 1993 6. Performing Organization Code
7. Author(s) Kent C. Kacir, H. Gene Hawkins Jr., Robert J. Benz, Mike E. Obermeyer, and Richard T. Bartoskewitz		8. Performing Organization Report No. Research Report 1297-2F
9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135		10. Work Unit No. (TRAIS) 11. Contract or Grant No. Study No. 0-1297
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Transfer Office P. O. Box 5080 Austin, Texas 78763-5080		13. Type of Report and Period Covered Final: September 1991 to August 1993 14. Sponsoring Agency Code

15. Supplementary Notes

Research performed in cooperation with the Texas Department of Transportation, the U.S. Department of Transportation, and the Federal Highway Administration.

Research Study Title: Guidelines for Flashing Traffic Signal Operation

16. Abstract

Operating traffic signals in the flashing mode is a viable alternative to normal (green-yellow-red) operation in many instances. Some of the common applications of flashing traffic signals include: for railroad preemption, in school areas, during low-volume periods, as the result of a signal malfunction, and prior to/following signal installation/removal. This report describes the research results of a two-year study on flashing traffic signals. The following activities are described in this report: a literature review of previous flashing signal research, a survey of current practice related to flashing signal operation, an operational analysis comparing flashing signal operation to other types of signal operation, and an investigation of accident trends. The findings from these activities were used to develop a series of guidelines addressing the conditions under which it is appropriate to place traffic signals in flashing operation, and the selection of the flashing mode (yellow/red or red/red).

17. Key Words Traffic Signals, Flashing Signals, Flashing Operation		18. Distribution Statement No restrictions. This document is available to the public through NTIS: National Technical Information Service 5285 Port Royal Road Springfield, Virginia 22161	
19. Security Classif.(of this report) Unclassified	20. Security Classif.(of this page) Unclassified	21. No. of Pages 268	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

EVALUATION OF FLASHING
TRAFFIC SIGNAL OPERATION

by

Kent C. Kacir, P.E.
Assistant Research Engineer
Texas Transportation Institute

H. Gene Hawkins, Jr., P.E., Ph.D.
Associate Research Engineer
Texas Transportation Institute

Robert J. Benz
Assistant Research Scientist
Texas Transportation Institute

Mike E. Obermeyer
Graduate Research Assistant
Texas Transportation Institute

and

Richard T. Bartoskewitz
Engineering Research Associate
Texas Transportation Institute

Research Report 1297-2F
Research Study Number 0-1297
Research Study Title: Guidelines for Flashing Traffic Signal Operation

Sponsored by the
Texas Department of Transportation
in Cooperation with the
U.S. Department of Transportation
Federal Highway Administration

November 1993

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

IMPLEMENTATION STATEMENT

These guidelines for flashing signal operation will assist TxDOT personnel in determining the appropriate conditions for changing from normal signal operation to flashing operation, and vice versa, so as to minimize delay and accident experience. These guidelines will provide more consistent application of flashing traffic signal operations in Texas, which may result in reduced delay and accident experience. The guidelines will also be useful to local officials by providing additional consistency in the use of flashing signal operations in Texas. The guidelines may eventually become part of the Texas *MUTCD*.

DISCLAIMER

ACKNOWLEDGEMENT

At the initiation of this study, an advisory committee was formed for consultation, review, and approval of all research activities encompassed by this study. The researchers would like to acknowledge those individuals participating in this capacity for their time and efforts:

Technical Panel Chairman

- Mr. Curtis Herrick, Traffic Operations Division, Texas Department of Transportation.

Technical Panel

- Mr. Paul Frerich, Yoakum District, Texas Department of Transportation.
- Mr. Steve Hill, Abilene District, Texas Department of Transportation.
- Mr. Jerry Keisler, Paris District, Texas Department of Transportation.
- Mr. Mike Leary, Federal Highway Administration.
- Mr. Bob Musselman, Federal Highway Administration.

TABLE OF CONTENTS

Page

continued

Page

continued

LIST OF FIGURES

continued

Figure Title Page

continued

continued

LIST OF TABLES

continued

continued

continued

SUMMARY

In some situations, flashing operation provides an effective alternative to operating a traffic signal in the normal (green-yellow-red) mode. When used, flashing operation typically converts a signalized intersection to a two-way or four-way stop controlled intersection by displaying a flashing yellow or flashing red indication to the various intersection approaches. Some of the more common uses of flashing operation include: during low-volume conditions, as part of railroad preemption, at signals in school areas, and during signal installation and/or removal.

There are two indications used in flashing operations - a flashing red and a flashing yellow. A flashing yellow indication allows vehicles to proceed through the intersection with caution. A flashing red indication operates as if it were a STOP sign. Flashing yellow indications cannot be shown to all approaches. Therefore, the two modes of flashing operation are yellow/red and red/red. Yellow/red flashing operation allows vehicles on the major street to continue through the intersection without stopping, while red/red flashing operation requires all vehicles to come to a stop at the intersection.

This two-year study of flashing signal operation is intended to answer two questions about flashing signal operation: 1) under what circumstances should signals be placed in flashing operation? and 2) when flashing operation is used, what flashing mode should be used? This report describes the activities and the associated findings related to flashing operation. These activities included: a review of pertinent literature, a survey of current flashing signal practices, an operational analysis comparing flashing signal operation to other types of signal operation, an analysis of the accident impacts associated with flashing operation, an evaluation of power savings resulting from flashing operation, an evaluation of driver behavior at intersections with flashing operation, and the development of guidelines for implementing flashing signal operation.

The literature review identified a number of previous research studies which evaluated some aspect of flashing operation. Most of these studies addressed the impact of flashing operation during nighttime periods on intersection accidents. The general conclusion of most of these studies is that the accident rate during nighttime flashing operation is higher than it would be with normal operation. However, there are a number of weaknesses in these studies. Many

base their conclusions on data from a limited number of intersections or for a limited period of time. The literature review also identified research which addresses other aspects of flashing signal operation. One of these areas is the power savings impacts of flashing operation. Previous studies have determined that flashing operation reduces the total energy consumption as compared to normal operation. The literature review also found that drivers facing a flashing red indication do not adequately understand that intersecting traffic may see a flashing yellow or a flashing red indication.

An evaluation of flashing signal practices was conducted to better identify the state-of-the-art in flashing signal operation. The evaluation included a survey of current practices in Texas, a survey of winter weather flashing practices in agencies which experience adverse weather, a review of previous surveys of flashing operations, and a review of the MUTCD principles for flashing operation. The Texas practices survey results indicate that flashing operation is a common practice and that it is used in a variety of circumstances. Unfortunately, most of the agencies do not have any formal guidelines for implementing flashing operation, nor have many of the organizations performed an analysis of flashing operation. The adverse weather survey did not identify any typical practices for the use of flashing operation during winter weather. The results indicated that few agencies use the flashing operation to reduce stops, whereas about the same number of agencies adjust signal timings during adverse weather conditions. The results of two other surveys from previous research studies are also described. The findings of an earlier survey parallel those of the survey given for this study. The other survey describes flashing signal practices at a number of cities in Texas.

The operational analysis of flashing operation compared the delay resulting from yellow/red and red/red flashing operation to the delay resulting from pretimed and actuated operation. Two computer simulation models were used to perform the analysis - TEXAS and TRAF-NETSIM. Total delay per vehicle was used as the measure-of-effectiveness. Simulations were conducted for various combinations of major and minor street volumes at an isolated intersection and for a three-intersection signal system. The analysis included the geometric shapes of 5×4, 5×2, 4×2, and 2×2. The results of the analysis indicate that yellow/red flashing operation has the lowest delay of any of the four types of signal operation, and in most cases the red/red flashing operation has the most delay. In general, yellow/red flashing operation appears to be appropriate when the major to minor street volume ratio is greater than three. The operational analysis also included a simulation of the diamond interchange. The analysis compared the fully actuated "figure 4" phasing arrangement to the yellow/red flashing operation. For the flashing operation, the arterial cross street received the yellow indication. The results indicate that yellow/red flash operation has the lowest delay by as much as one-half the delay of the actuated operation.

The accident analysis compared accident records for flashing, non-flashing, and before/after signalized intersections. Flashing locations operated continuously over the study period and non-flashing locations did not flash during the study period. Before/after study sites included two years of flashing operation and two years of normal operation. The analysis was limited to signalized intersections with four perpendicular approaches, and bi-directional traffic flow. Over two-hundred intersections were identified and analyzed. The analysis indicated that accidents typically increase with flashing operation. However, the analysis also indicated that those intersections which had zero accidents during nighttime flashing operation also had zero accidents during the two-year period of normal operation.

Supplementary analyses were performed for signal power consumption during flashing operation, nighttime driver behavior at signalized intersections, and comparisons of nighttime hourly volumes to daily volumes. The power consumption analysis indicated that only slightly less power is consumed during flashing operation than other types of signal operation. Nighttime driver behavior was observed at intersections operating in the four types of signal control. Drivers tend to "roll through" approaches with the flashing red signal. Generally there were more violations for pretimed signal control than actuated signal control. Traffic volume data from over 200 data sets indicated anticipated traffic volumes between 9 pm and 6 am hours of the day. This analysis is useful to augment the operational findings and graphical trends.

The findings as described above were used to prepare a series of guidelines intended to assist transportation professionals in evaluating the need to implement flashing operation. These guidelines address the use of flashing operation for the following circumstances:

Low-Volume Periods
Signal Installation
Signal Removal

Emergency (Conflict)
Railroad Preemption
School Area

The findings were used to develop a flowchart for implementing nighttime flashing operation. Due to the operational flexibility provided by actuated signal control, flashing operation should only be used with pretimed signal control. Typically, flashing operation may be considered when the highest major street approach volume is less than 250 vehicles per hour (vph), the highest minor street approach volume is less than 100 vph, the volume ratio is three or more, and there have been no or one accident during the most recent two-year period. The guidelines for low-volume flashing operation include a flowchart which can be used in evaluating the appropriateness of implementing flashing operation.

In some situations, flashing operation provides the only effective means of controlling traffic when normal operation cannot be used. These situations include: signal installation and removal, emergency flash, railroad preemption, and school area signals.

CHAPTER 1
INTRODUCTION

Traffic signals provide a safe and effective means of controlling traffic and pedestrians at intersections. However, because they assign the right-of-way to the various traffic movements at an intersection, traffic signals exert a profound influence on traffic flow. Section 4C-2 of the *Texas Manual on Uniform Traffic Control Devices* (TMUTCD or Texas MUTCD) (1) states that signals "*should neither be put into operation nor continued in operation*" unless one or more of the signal warrants described in the TMUTCD are met. The volume warrants require a minimum traffic volume to be present for at least eight hours of the day. However, even when an intersection meets one of the warrants, there may be time periods when traffic volumes are below the warrant levels. In these situations, operating the signals in a flashing mode may be an alternative to operating the signals in the normal (green-yellow-red) mode. The primary justification for flashing operation is that vehicular delay can be reduced by eliminating or reducing the number of stops. In general, flashing operation becomes feasible when traffic volumes decrease to the point that the minor street traffic can complete the desired maneuver almost immediately upon arriving at the intersection.

With flashing traffic signal operation, a flashing yellow or flashing red indication is shown to drivers approaching the intersection. The flashing yellow is commonly given to the major street approaches and the flashing red to the minor street approaches. Sometimes it is appropriate to show a flashing red indication to all approaches. A flashing yellow is never shown to conflicting approaches. Vehicles approaching the flashing yellow do not have to stop, thereby reducing delay to those vehicles. The flashing red operates the same as a STOP sign, and the length of the time that the vehicle is stopped is determined by the presence of gaps in the conflicting traffic. As a result, flashing operation has the potential to significantly reduce vehicular delay in certain situations. The simplicity of its operation also makes it useful in a variety of situations.

Characteristics of Flashing Traffic Signals

A flashing traffic signal is any traffic control signal which intermittently illuminates the yellow or red lens in the traffic signal face. Section 4B-18 of the TMUTCD (1) states that the illuminating element in a flashing signal shall be flashed continuously at a rate of not less than 50 nor more than 60 times per minute. The same section also states that the illuminated period of each flash shall not be less than half and not more than two-thirds of the total flash cycle.

Uses of Flashing Traffic Signals

Flashing traffic signals have application in a variety of different circumstances. In each of these situations, the advantages of flashing operation provide an alternative to operating the signals in the normal mode. Some of the most common applications of flashing operation are described below. Specific guidelines for the use of flashing signals in these applications are described in Chapter 7.

Low-Volume Periods

During some portions of a 24-hour period, the traffic volumes at an intersection may decrease to the level where it may not be efficient or appropriate to operate signals in the normal mode. These low-volume periods typically occur between the hours of 10:00 pm and 6:00 am, although there may be other circumstances where low-volume conditions may be present. During these low-volume periods, the signals may be placed in flashing operation to reduce vehicular delay. The majority of effort in this research study is focused upon the development of guidelines for the use of flashing operation during low-volume, nighttime periods.

Signal Installation

The initial operation of a new traffic signal installation is a critical period as drivers are adjusting their driving habits to the presence of a new traffic signal. Therefore, a new signal is often placed in flashing operation during the period between when the installation is completed and the first operation in the normal mode. This allows motorists to become aware of the presence of the signal and notifies them that the signal, which has been inactive during construction, is completed and operating.

Signal Removal

Traffic patterns change and sometimes it becomes desirable to remove a signal. When this is the case, the signal is often placed in flashing operation prior to removal to insure that the intersection will operate satisfactorily without the assistance of a signal.

Emergency Flashing

Emergency flashing occurs when the signal's conflict monitor is activated (either manually or automatically) and the signal changes from normal to flashing operation. Emergency flashing is also referred to as conflict flashing. The conflict monitor is activated by detecting the presence or absence of voltages at field terminals. This prevents the display of conflicting signal indications and provides the ability to prevent operation of a signal when the signal lamps have gone out. Emergency flash may also be used when the signal controller is undergoing maintenance activities.

Adverse Weather

Periods of adverse weather can have a significant impact on traffic flow. In particular, the presence of snow or ice on the roadway may create some difficulties in stopping and starting vehicles. Fog may also reduce the visibility of the traffic signal. Therefore, traffic signals may be placed in a flashing mode during some periods of adverse weather.

Railroad Preemption

Traffic signals located near a railroad-highway grade crossing cannot operate in the normal manner when a train is present. The signal operation must give proper right-of-way to the train. At these intersections, the signal controller is connected to the railroad crossing controller which detects the approach of a train. The detection activates a special railroad preemption phase which clears vehicles stopped over the track and then stays in a specified control mode for as long as the train is over the crossing. The preemption control mode may display a red indication to all approaches, use yellow/red or red/red flashing operation, or display a green indication to the intersection approach(es) not conflicting with the grade crossing.

School Areas

Traffic signals installed in school areas may only be needed during the time periods immediately before and after school. They may present an unnecessary hindrance to traffic flow during other times, and as a result, they may be set in flashing operation when school children are not present.

Modes of Flashing Signal Operation

There are two modes of flashing signal operation: yellow/red and red/red. Yellow/red flashing operation permits two approaches with the same directional orientation to travel through the intersection with caution, and the remaining approaches are required to come to a complete stop. Yellow/red flashing operation functions in a manner similar to an intersection controlled by two-way STOP signs. Red/red flashing operation requires vehicles on all approaches to come to a stop before entering the intersection. Red/red flashing operation functions in the same manner as if the intersection was controlled by a four-way STOP sign.

Flashing Signal Issues

The decision to change a traffic signal from normal to flashing operation can be a difficult one which requires the consideration of many different factors. Some of the more significant factors which the traffic engineer must consider include:

- The traffic volume level at which flashing operation becomes effective,
- Selection between yellow/red or red/red flashing modes,
- The impact of accidents on the implementation of flashing operation,
- The impacts of geometrics and sight distance on the implementation of flashing operation,
- The influence of pretimed control versus actuated control on the effectiveness of flashing operation,
- Driver understanding and violation of flashing signal operation,
- The potential electrical energy savings which can be realized from flashing operation,
- The need for flashing operation during adverse weather conditions, and/or
- The relationship between normal flashing operation and emergency flashing operation.

Intersection Control Beacons

The intersection control beacon is a special type of traffic signal which displays only a flashing circular red or flashing circular yellow indication to the approaching traffic. Intersection control beacons do not display a green indication at any time. They are intended for use at intersections where traffic or physical conditions do not justify conventional traffic signals, but where high accident rates indicate a special hazard.

When a conventional traffic signal is operating in the flashing mode, it functions in a manner very similar to an intersection control beacon. However, due to differences in the basis for installing these two types of signals, issues and guidelines related to flashing operation of conventional signals cannot be broadly applied to intersection control beacons. This research study **does not** address intersection control beacons due to the application and operational differences between beacons and flashing signals.

Description of Research Study

The use of flashing operation is relatively common. The existing guidelines for implementing flashing operation are limited in their application and are not widely used in Texas. Instead, the decision to use flashing signal operation is based primarily on engineering judgement. As a result, there is inconsistent use and application of flashing signal operation. Recognizing the need to evaluate the operations of flashing traffic signals, the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA) have jointly sponsored this research study of flashing traffic signals.

Study Objectives

The objective of this study is to develop guidelines for the use of flashing traffic signals. These guidelines are intended to answer two fundamental questions:

1. Under what circumstances should traffic signals be placed in flashing operation?
2. When flashing operation is used, what flashing mode (color indications) should be displayed to the various approaches and turning movements?

Research Approach

This two-year study utilized scientific evaluation methods to examine flashing traffic signal operation. During the course of the study, a number of research activities were undertaken in an effort to collect information on flashing traffic signal operation. The major study activities included the following:

Literature Review

As with any research effort, the first step in this study was to develop a common base of knowledge. A detailed review of previous research and literature addressing flashing signal operation was used to establish the state-of-the-art and identify the conclusions and recommendations of others. In particular, the literature review was intended to identify the factors which others have used to decide when to convert to or from flashing operation. The results of the literature review are described in Chapter 2 of this report.

Existing Guidelines and Current Practices

The second activity of this study was to identify existing guidelines and current practice related to flashing operation. This effort included a review of MUTCD guidelines for flashing operation, a survey of flashing signal practices in TxDOT districts and Texas cities, a survey of adverse weather flashing practices, and a description of flashing signal practices in local and state agencies. Responses to the Texas practices survey were received from all 24 TxDOT districts and 23 local transportation agencies in Texas. These surveys identified how flashing operation was used with traffic signals, the guidelines that the various agencies used to implement flashing operation, the impacts of flashing operation, and the location of potential study sites for the survey. Responses to the adverse weather survey were received from 28 agencies located in cold weather areas. The descriptions of existing guidelines and current practices are contained in Chapter 3.

Operational Analysis

There are a number of difficulties associated with evaluating the operation of flashing traffic signals. In particular, data collection is more difficult for a number of reasons. Since most low-volume periods occur during periods of darkness, it is difficult to use video or photography to collect data. Also, the traffic volumes during these periods are very low, and this makes it difficult to obtain sufficient data to represent a broad variety of operational conditions. Therefore, two computer simulation programs were used to evaluate flashing signal operation with respect to some of the major issues addressed in this study. The results of the operational analysis are described in Chapter 4.

Accident Analysis

Driver safety is one of the primary concerns associated with the use of flashing traffic signals. Flashing operation cannot be effectively implemented if it results in an increase in accidents attributable to flashing operation. The importance of the safety concern is evidenced by the fact that several of the previous studies of flashing operation have concentrated on this aspect. A rigorous evaluation procedure was used in this study to assess the safety implications of flashing operation. The results of the accident analysis are described in Chapter 5 of this report.

Supplemental Research Activities

The decision to implement flashing signal operation should be based on more than just operational and safety issues. This study also evaluated several other factors which should be considered in the decision. These factors include: 1) power savings resulting from flashing operation, 2) driver behavior at flashing signals, and 3) the relationship between nighttime traffic volumes and 24-hour volumes. These issues are described in Chapter 6.

Flashing Signal Guidelines

The results of the first and second year activities were evaluated and used to develop guidelines for flashing traffic signal operation. These guidelines are based upon the findings of the literature review, the surveys of current practice, the operational analysis, the accident analysis, and the analysis of other issues. The guidelines for implementing flashing operation are summarized in a series of easy-to-use flowcharts which diagram the decision making process. More detailed descriptions of the guidelines are also included in the report. Chapter 7 contains the flowcharts and the detailed descriptions of the guidelines.

Definitions

Definitions for technical terms used in this report are provided in Chapter 8. These definitions are provided in order to ensure that guidelines and other statements are interpreted in the desired manner.

CHAPTER 2

LITERATURE REVIEW

Flashing operation of traffic signals has been a concern of traffic engineers for many years. As far back as 1935, the MUTCD (2) contained recommendations on the use of flashing signal operation. Unfortunately, these recommendations appear to be based on engineering judgement instead of scientific research and the MUTCD guidelines have subsequently changed several times. The search for practical and reliable guidelines has continued over the years in several research studies of flashing operation. Therefore, a key task of this study was to review these previous studies of flashing signal operation in order to identify the major issues which have been evaluated in the past. Research findings addressing flashing signal operation were identified and reviewed for applicability to this study. The review identified numerous issues which have an impact on the decision to implement flashing operation. These issues include: accidents, volume ratio, environmental impacts, time of flashing operation, driver comprehension of flashing signal indications, delay/stops, and conflict flashing. The findings of these studies address a wide variety of conditions, and in some cases, the findings conflict with one another.

Description of Previous Studies on Nighttime Flashing

The use of low-volume or nighttime flashing traffic signal operation has been evaluated in several previous research efforts. Most of these studies developed one or more guidelines related to the use of flashing operation. Some guidelines identify when flashing operation becomes feasible, while other guidelines identify when flashing operation should be discontinued. Most of these guidelines use accidents, traffic volume, time of day, and/or delay as the basis for evaluating flashing operation. This section provides a general description of some of the major research studies on flashing operation and identifies the type of guidelines which resulted from each study. The specific findings of each study are described in the next section so that findings based on the same factors can be compared to one another.

Washington, D.C. Study, 1966

A study (3) conducted by the District of Columbia in the early 1960's analyzed accidents at 741 intersections with nighttime flashing operation. Of these, 162 were converted to 24-hour normal operation. Five months of before data for the nighttime period were compared to five months of after data for the same time period. The study results indicated that total accidents decreased by about 40 percent at the intersections converted to normal operation. This study only looked at accidents, and it concluded that accidents could be reduced by placing intersections on 24-hour normal operation.

Los Angeles County Study, 1972

A study (4) by Los Angeles County evaluated accidents at 18 intersections that changed from nighttime flash to 24-hour normal operation. These 18 intersections included 16 that were converted from nighttime yellow/red flashing operation to 24-hour normal operation and two intersections that were converted from red/red flashing to normal flashing. The study only evaluated accidents. One year of before accident data were compared to one year of after accident data. The study concluded that accidents could be reduced at some intersections by converting from nighttime flashing to 24-hour normal operation. The study further concluded that the accident rate for flashing operation is related to the accident rate for normal operation.

Marson's Thesis, Michigan State University, 1976

A thesis written by Joseph Marson for a Master of Science degree at Michigan State University (5) compared accidents at 99 intersections with nighttime flashing operation to accidents at 70 intersections with 24-hour normal operation. The intersections were located throughout Michigan. The intent of the study was to determine the effect of signal control on accidents. The accident data was categorized by accident type, volume ratio, intersection geometry, speed limits, and signal interconnection. The accident analysis indicated those categories where the accident rate for flashing operation was significantly higher or lower than for normal operation. The results did not indicate a clear advantage of one signal operation over the other. However, the results did indicate where flashing operation under various combinations of factors may reduce the potential for certain types and severities of accidents.

Federal Highway Administration Study, 1980

The most comprehensive study of flashing traffic signal operation was conducted in the late 1970's as part of an FHWA study of traffic signal operation. The four-volume series of reports was entitled *A Study of Clearance Intervals, Flashing Operation, and Left-Turn Phasing at Traffic Signals* of which Volume 3 (6) specifically addresses flashing signal operation. This FHWA study evaluated flashing signal operation from the standpoint of available literature, a survey of state laws, a survey of state and local traffic engineers, a survey of motorists, an analysis of fuel consumption and vehicle emissions, and field studies of accident conflicts, violations, speed, and delay. The guidelines developed in this research study address flashing operation from the standpoint of volume, volume ratio, accidents, and mode of flash. Some of the findings from the survey of traffic engineers are described in Chapter 3 of this report, and findings related to the operational analysis are described in Chapter 4.

Oakland County, Michigan, 1983 and 1987

Oakland County, Michigan, (which includes a portion of Detroit) has performed two studies of flashing operation. The first study, which is described in two different papers (7, 8), evaluated accidents at six intersections where flashing operation had been discontinued. Three years of before accident data were compared to three years of after data. The before and after study evaluated accident type, traffic volume, volume ratio, drinking involvement, and time of night. The study also compared accident rates for intersections with flashing operation to similar intersections with normal operation on the basis of functional classification. The study concluded that accidents could be reduced by eliminating flashing operation during nighttime periods. The second study (9) was a follow-up to the first. In the second study, four years of accident data for nighttime flashing operation were compared to 1¾ years of accident data for 24-hour normal operation at 59 intersections. The second study only evaluated right-angle and rear-end accidents and reconfirmed the findings of the first study.

Portland, Oregon, 1984

In 1984, Oregon State University (10) analyzed flashing signal operation at 30 intersections in Portland, Oregon, where flashing operation had been discontinued. The study compared before and after accident data of one or two years for each the following categories: volumes, street classifications, types of approach (one- or two-way), speed limits, and parking. The analysis evaluated both accident type and accident severity. Accident rates were used as the basis of comparison. The guidelines developed from this study address the volume ratio, approach speed, type of approach, and visibility. The study found that accidents were higher for flashing operation in certain circumstances.

Findings of Previous Research on Nighttime Flashing Operation

Most of the studies that have evaluated nighttime flashing operation have focused on accident aspects of flashing. Other studies have also looked at other aspects of flashing operation. Previous research efforts reviewed for this study address the effectiveness of nighttime flashing from the standpoint of: accidents, volume ratio, volumes, environmental impacts, time of night, driver comprehension, mode of flashing operation, and delay.

Accidents and Flashing Operation

Accidents are a major concern related to flashing operation. Therefore, it is not surprising that many studies have evaluated the impacts of flashing operation with respect to accidents. Guidelines based on accidents typically specify a threshold level (either accident frequency for a given period or an accident rate). If the accidents exceed this threshold value, then flashing operation should not be implemented or should be discontinued. Accident-based guidelines are also commonly associated with some volume-based criteria or other traffic parameters. The general results of accident evaluations are described in the following paragraphs. Chapter 5 includes a detailed review of the evaluation procedures used in these studies.

The 1966 District of Columbia study (3) evaluated before-and-after accident patterns at 714 intersections which used nighttime flashing operation. These intersections were divided into three groups: Group I - 162 intersections that were converted from nighttime flashing to 24-hour normal operation, Group II - 177 intersections which continued to use nighttime flashing operation and which were within two blocks of Group I intersections, and Group III - 402 intersections which continued to use nighttime flashing operation and which were at least two blocks away from Group I intersections. Accidents for a five-month period before the change were compared to accidents for the same five-month period one year later. The results of the study are shown in Table 2-1.

Table 2-1. Washington, D.C. Accident Analysis (3)

Accident Type	Number of Intersection Accidents (5 month period)								
	Group I[1]			Group II[2]			Group III[3]		
	Flash	Normal	Percent	Before	After	Percent	Before	After	Percent
All Accidents	64	35	-45.3	70	46	-34.3	105	99	-5.7
Angle Collision	41	15	-63.4	49	26	-46.9	62	63	+1.6
Personal Injury Accidents	22	10	-54.5	22	17	-22.7	44	41	-6.8
Property Damage Accidents	42	25	-40.5	48	29	-39.6	61	58	-4.9

Notes:
[1] Intersections which changed from flashing to normal operation.
[2] Intersections within two blocks of Group I intersections which continued flashing operation.
[3] Intersection more than two blocks from Group I intersections which continued flashing operation.

This study concluded that accidents could be reduced by placing signals on 24-hour normal operation. However, the study did not consider the impacts of delay incurred by vehicles required to stop at the signals, nor did it consider driver compliance with a red indication when no other traffic was at the intersection.

The FHWA study (6) included an analysis of accidents as part of the research effort. Two different accident analyses were performed. The first analyzed accidents in the San Francisco area occurring over a 40-month period. During that time, San Francisco was in the midst of a major program to convert a large proportion of its signals to nighttime flashing operation. The results of the San Francisco analysis are summarized in Table 2-2. The second analysis compared accidents from several cities during a three-year period of 24-hour normal operation to accidents during a one-year period after there was a change to flashing operation. Only intersections which changed from normal operation to yellow/red flashing were included in the analysis. The results are summarized in Table 2-3.

The accident analysis in the FHWA study found that, in general, yellow/red flashing operation increased the rate of accidents. The exception was at intersections with a volume ratio equal to or greater than 3 or where major street two-way volume was less than 200 vehicles per hour during flashing operation. The FHWA study recommended an accident-based guideline for eliminating flashing signal operation. The guideline stated that yellow/red flashing operation should not be used if the following accident levels are reached or exceeded at an intersection:

Table 2-2. FHWA San Francisco Accident Analysis (6)

Type of Change		No. of Intersections	Accident Severity			Type of Accident		Total Accidents
Before	After		Fatal	Injury	Property Damage Only	Rear-End	Angle	
Normal Operation	Y/R Flash	375	0 <.005	.09 .20*	.09 .27*	.02 .04	.13 .40*	.18 .48*
Normal Operation	R/R Flash	36	0 0	.16 .11	.02 .21	0 .04	.18 .23	.18 .31
Normal Operation	Normal Operation	107	0 0	.16 .16	.17 .17	.06 .03	.22 .24	.33 .33
Y/R Flash	R/R Flash	2	0 0	1.39 0	.79 1.23	.20 0	1.59 1.23	2.18 1.23
All Intersections		520	0 <.005	.11 .19*	.10 .25*	.03 .04	.16 .36*	.22 .44*

Notes: Accidents expressed as BEFORE/AFTER (accidents/year/intersection)
Y/R=Yellow/Red flash, R/R=Red/Red flash
*Indicates statistically significant increase at ρ=0.05 level of significance

Table 2-3. FHWA National Accident Analysis (6)

Type of Analysis	No. of Intersections	Accident Severity			Type of Accident		Total Accidents
		Fatal	Injury	PDO	Rear-End	Angle	
Rate/Million Vehicles	55	0 0	.99 .99	1.58 3.37	.77 .68	.64 2.34*	2.66 4.44*
Total Number of Accidents	58	0 0	13 34	37 104	21 31	15 59	72 158

Notes: Accidents expressed as NORMAL/FLASH for all intersections
*Indicates statistically significant increase at ρ=0.05 level of significance

- Three right-angle accidents in one year during flashing operation (short-term rate),
- Two right-angle accidents per million vehicles during flashing operation, if the rate is based on an average of three to six observed right-angle accidents per year (long-term rate), or
- 1.6 right-angle accidents per million vehicles during flashing operation, if the rate is based on an average of six or more right-angle accidents per year (long-term rate).

The 1972 Los Angeles County study (4) looked at accidents for intersections that changed from nighttime flashing operation to 24-hour normal operation. Accidents for a one-year before period were compared to a one-year after period at 18 intersections. The 18 intersections were also split into seven "high" and eleven "low" accident locations for the before period. The accident frequencies are shown in Table 2-4. The study concluded that operating pretimed signals 24 hours a day, instead of using flashing operation during light traffic hours, may reduce accident and injury experience, especially at locations where a high incidence of accidents has been found during the flashing period. The study further suggested that locations with low accident experience during the flashing operation will not have increased accident experience during the same time period if the signals are placed on 24-hour operation.

Table 2-4. Los Angeles Accident Analysis (4)

Type of Signal Operation	Number of Accidents								
	7 "High" Before Accident Intersections			11 "Low" Before Accident Intersections			All 18 Intersections		
	Angle	Rear-End	Total*	Angle	Rear-End	Total*	Angle	Rear-End	Total*
Flash (Before)	21	2	35	1	2	3	33	4	38
Normal (After)	5	7	15	1	2	3	6	9	18

Notes: Accidents are for both periods are for the time period when the before intersections were on flash.
Before and After periods were each one year.
*Total accidents includes other types not shown in table.

The 1983 Michigan study (7, 8) of accidents at intersections with flashing operation found that nighttime accident rates were higher for intersections with flashing operation. The study evaluated three years of before and three years of after accident data at 6 intersections where nighttime flashing operation had been discontinued. It also compared accidents at 82 additional intersections with nighttime flashing operation with 21 intersections with 24-hour normal operation. Table 2-5 summarizes some of the accident analysis from this study. The following conclusions were drawn from the accident analysis:

Table 2-5. First Oakland County, Michigan, Accident Analysis (7, 8)

Condition	Right-Angle Accidents	
	Accidents/Yr-Hr of Signal Operation	Accidents/Million Vehicles
Before (flash)	0.824	81.52
After (normal)	0.125	1.82

1. The rate of right-angle accidents for volume ratios less than or equal to two were significantly higher that the rate for ratios of four or more at flashing intersections.
2. Hourly intersection traffic volume had a negligible impact on right-angle accident frequency during hours of flashing operation.
3. Drinking involvement was significantly over-represented in right-angle accidents at flashing signal locations.
4. Right-angle accidents at flashing locations peaked between midnight and 3:00 am, after which they dropped dramatically. Right-angle accidents at normal locations peaked between 2:00 and 3:00 am. It should be noted that bars in the area closed at 2:00 am.

This study criticized the accident-based guidelines in the FHWA study (6) (eliminating flashing operation on the basis of a specified accident rate), stating that the guidelines were erroneously based on the critical levels of right-angle accident frequency and rate at flashing signal intersections instead of the right-angle accident experience of normal operation intersections. The major conclusion of this study was that eliminating nighttime flashing operations at four-leg intersections of two arterial roads appears to be effective in reducing right-angle accident frequency. The study also recommended removing flashing signal operation when the volume ratio is less than four.

The 1983 Michigan study was expanded upon in 1987 (9). The second study compared accidents at 59 intersections which converted from nighttime flashing to normal operation. Four years of before accident data were compared to 1¾ years of after data. The results of the analysis are summarized in Table 2-6. The analysis of accidents confirmed the findings of the first study, indicating that right-angle accidents can be reduced by converting signals with nighttime flashing operation to 24-hour normal operation.

Table 2-6. Second Oakland County, Michigan Accident Analysis (9)

Accidents per Year		Total	Fatal	Injury
Right-Angle Accidents	Before (flash)	50.50	0.75	31.00
	After (normal)	4.57	0.00	1.71
Rear-End Accidents	Before (flash)	7.75	0.00	2.25
	After (normal)	10.29	0.00	1.75

Volume Ratio and Flashing Operation

The ratio of the major street volume to the minor street volume has been used in several studies to determine the impacts of traffic volumes on accidents at intersections with flashing operation.

The Michigan State University thesis (5) compared accidents at 99 intersections with low-volume flashing operation to 70 intersections with 24-hour normal operation. The comparison found that there was no significant difference in total accident rates, but when the accidents were classified by the major to minor average daily traffic (ADT) ratio, it found a significant difference in accident rates. The relationship between accident rates and the volume ratio are shown in Table 2-7.

Table 2-7. Comparison of Accidents by Volume Ratio (5)

Variable		Total Accident Rate[1]		Rear-End Accident Rate		Angle Accident Rate		Property Damage Accident Rate	
		Flash	Normal	Flash	Normal	Flash	Normal	Flash	Normal
All Intersections		2.78	2.42	0.55	0.96*	1.16	0.61	1.57	1.54
Volume Ratio[2]	< 2	2.91	2.36	0.28	0.83*	1.33	0.73	0.92	1.55*
	2 - 4	3.20	2.21	0.63	0.94	1.46*	0.45	2.03	1.24
	> 4	2.22	3.31*	0.62	1.63*	0.71	0.50	1.40	2.35*

Notes: [1]Accident Rate is accidents per million vehicles for the period 12:00-6:00 am
[2]Volume Ratio = Major St. ADT/Minor St. ADT
*Indicates group with significantly higher accident rate at $\rho=0.10$ level of significance

The table shows that there was a significant statistical difference in the accident rate for several categories at intersections where the volume ratio is greater than four, with flashing operation being the safer of the two. When the volume ratio is between two and four, the data indicated that intersections with flashing operation have a statistically higher accident rate for right-angle accidents. These data also indicate that, in general, accident rates are higher with flashing operation than normal operation, although the differences may not be statistically significant.

The second accident analysis (national data) in the FHWA study (6) analyzed accidents with respect to the volume ratio. Accidents at 59 intersections where 24-hour normal operation was converted to nighttime flashing operation were categorized by the hourly volume ratio during the nighttime hours. Three years of before accident data were compared to one year of after data. The results of the analysis are shown in Table 2-8. The analysis found that there is a significant increase in right-angle accidents when the volume ratio is between two and three, leading to the conclusion that use of flashing operation with a volume ratio of less than three would seem to significantly increase the likelihood of right-angle accidents.

Table 2-8. FHWA National Volume Ratio Accident Analysis (6)

Variable		No.	Total Accident Rate[1]		Rear-End Accident Rate		Angle Accident Rate	
			Flash[2]	Normal[3]	Flash	Normal	Flash	Normal
All Intersections		55	4.44	2.66	0.68	0.77	2.34	0.64
Volume Ratio	< 1	5	6.45	5.11	0.91	1.46	2.79	0.91
	> 1 & ≤ 2	10	5.99	3.62	0.49	0.77	4.06	1.45
	> 2 & ≤ 3	12	2.86	0.57	0.34	0.12	2.17*	0.00
	> 3 & ≤ 4	4	1.69	1.90	0.00	1.27	0.85	0.63
	> 4 & ≤ 5	5	4.20	1.36	0.00	0.39	2.51	0.00
	> 5 & ≤ 10	8	0.94	2.20	0.00	0.96	0.23	0.33
	> 10	9	2.12	0.40	1.55	0.19	0.27	0.21

Notes: [1] Accident Rate is accidents per million entering vehicles
[2] Intersections on nighttime flash
[3] Intersections on 24-hour normal operation
*Indicates group with significantly higher accident rate at $\rho=0.05$ level of significance

The accident analysis in the first Michigan study (7, 8) also looked at the volume ratio and determined that the accident rate for right-angle collisions at intersections with nighttime flashing operation is higher when the ratio is less than two than when the ratio is greater than four. However, the descriptions of this study do not include specific analysis results to support the conclusion.

The Portland, Oregon study (10) analyzed accident data for 30 intersections where nighttime flashing operation had been replaced with 24-hour normal operation. Although it is not stated in the study description, it is assumed that the signals operated in a yellow/red flashing mode. The before-and-after analysis compared one to two years of accident data for each type of operation. The accident severity and accident type were analyzed according to volume ratio, street classification, one- or two-way approach, speed limit, and presence of parking. Table 2-9 summarizes the findings of the analysis relative to traffic volume ratio. The researchers used these results to conclude that flashing operation with a volume ratio of two to four is unsafe. They recommended that flashing operation be used when the volume ratio is less than two.

Table 2-9. Portland, Oregon Volume Ratio Accident Analysis (10)

Variable		No.	Total Accident Rate[1]		Rear-End Accident Rate		Angle Accident Rate	
			Flash[2]	Normal[3]	Flash	Normal	Flash	Normal
Volume Ratio	< 2	4	1.06	3.29	—	—	—	—
	2 - 4	14	5.44*	1.20	1.60	0.47	3.30*	0.00
	> 4	12	2.76	1.89	0.00	0.41	2.21*	0.43

Notes: [1] Accident Rate is accidents per million entering vehicles
[2] Intersections on nighttime flash
[3] Intersections on 24-hour normal operation
*Indicates group with significantly higher accident rate at $\rho=0.05$ level of significance

Traffic Volume and Flashing Operation

Traffic volume has also been used as a parameter for evaluating the feasibility of flashing operation. For flashing operation to be feasible, volumes should be low enough so that vehicles required to stop will not incur significant delay while waiting for a gap in the cross-street traffic. Flashing guidelines based on traffic volume can take any of the following forms:

- One-way or two-way volume below a prescribed level.
- Volume less than a percentage of the warrant volume.
- Ratio of major to minor street volume.
- Period of time (usually the number of hours) that the reduced volume exists.

The national accident analysis of the FHWA study (6) looked at the impacts of volume on accidents by grouping accidents according to the major street two-way volume during the first hour of flashing operation. Table 2-10 summarizes the results of the analysis. By combining the results of the volume and volume ratio analysis, the FHWA study developed the following volume-based guidelines for flashing signal operation. These guidelines assume that pretimed controllers are used.

Table 2-10. FHWA National Volume Based Accident Analysis (6)

Variable		No.	Total Accident Rate[1]		Rear-End Accident Rate		Angle Accident Rate	
			Flash[2]	Normal[3]	Flash	Normal	Flash	Normal
All Intersections		55	4.44	2.66	0.68	0.77	2.34	0.64
Major Street 2-Way Volume During the 1st Hour of Flashing Operation (vph)	≤ 50	13	2.99	1.06	0.16	0.00	2.60	0.84
	> 50 & ≤ 100	10	4.34	0.65	1.39	0.00	2.94	0.36
	> 100 & ≤ 150	12	1.77	2.46	0.54	0.74	0.00	0.38
	> 150 & ≤ 200	7	4.67	4.08	0.70	1.62	2.46*	0.00
	> 200 & ≤ 250	2	7.77	2.63	0.00	1.91	5.87*	0.00
	> 250	9	3.23*	2.29	0.00	0.97	0.96	0.79

Notes: [1] Accident Rate is accidents per million entering vehicles
[2] Intersections on nighttime flash
[3] Intersections on 24-hour normal operation
*Indicates group with significantly higher accident rate at $\rho=0.05$ level of significance

- Yellow/red flashing operation may be used when two-way traffic volumes on the major street are below 200 vph.
- Yellow/red flashing operation may be used where the two-way major street volume is greater than 200 vph provided the ratio of major street volume to minor street volume is greater than three.

The findings of the first Michigan study (7, 8) relative to traffic volume contradict those of the FHWA study (6). Right-angle accidents were compared for various volume categories, and the analysis indicated that hourly intersection traffic volume had a negligible impact on accidents during flashing operation. Once again however, the study report does not provide any data to support this conclusion.

Environmental Impacts of Flashing Operation

Flashing traffic signals have the potential to help the environment in three ways. A reduction in delay and stops will reduce fuel consumption. The electrical power consumed by the traffic signal will be reduced because the signal lamps are lit only half to two-thirds of the time and pedestrian signals are not used when a signal is flashing. Finally, the benefits of the reduced fuel emissions of carbon monoxide, hydrocarbons, and oxides of nitrogen have the potential to render higher quality air and a reduction in the possibility of acid rain.

The City and County of San Francisco (11) estimated that system-wide traffic signal electrical consumption could be reduced by 10 percent by placing 670 of their 840 signals in flash from midnight to 6:00 am. They also estimated that they could save 450,000 gallons of gasoline and reduce delay by 540,000 vehicle-hours per year. This study estimated that electrical costs to operate flashing signals are almost half of the amount that it would cost to operate signals in normal operation.

The most comprehensive evaluation of the environmental impacts of flashing operation is in the 1980 FHWA report (6). The study looked at fuel consumption, vehicle emissions, and electrical power consumption. The study concluded that:

- The type of flashing operation affects the total energy consumption if fuel consumption is looked at along with the electrical energy consumption. Red/red flashing operation was found to use more energy than yellow/red flashing operation.
- The use of flashing signals can save money by reducing motorist delay. There are several factors that should be considered in the fuel conservation analysis: 1) vehicle deceleration, 2) stop delay or idle time delay, and 3) start-up delay or the energy it takes to accelerate to the running speed.

The FHWA study found that as the speed of the approach increases, the fuel consumption and emissions also increase. As the volume ratio increases, the emissions are reduced. The study indicated that the fuel savings for a nationwide conversion to flashing operation are quite astounding. If the approach speed for all signals is assumed to be 30 mph (50 km/h) and all the signals in the nation were converted to flashing operation, the result would be a savings of 10.7 million gallons of fuel a year. The study further assumed that if only those intersections with a volume ratio greater than 3 were put on flashing, then 18.6 million gallons of gasoline could be saved. The study stated that the fuel emission impact of flashing operation is difficult to determine, but it is expected to be a substantial benefit. The study mentioned that it seems strange that more fuel could be saved by putting fewer signals on flash. This discrepancy was explained by the fact that pretimed signals in a network use less fuel than flashing yellow/red operation when the volume ratio is less than three.

An Albuquerque, New Mexico, report (12) examined different low-cost methods of saving fuel. It was found that fuel consumption was minimized at a speed of 30 to 35 mph (50-55 km/h). This report suggested that possible ways to maintain this speed range are: one-way streets, signal coordination, removal of STOP signs, installation of right turn lanes, and implementing flashing signal operation (implied as yellow/red flashing). It was suggested that the implementation of flashing signal operation, "provided the most benefit for the least cost." The analysis was conducted with a regression model and proved to be fairly reliable. The low-cost traffic improvements are not as beneficial as van pools, reduced travel, or improved vehicles, but they are beneficial and are in use throughout the day.

Time of Night and Flashing Operation

The FHWA report (6) found that in all instances of significance, there was a disproportionately higher number of accidents in the hour between 2:00 and 3:00 am. At the San Francisco site used in this study, this was the hour just after it was illegal to sell alcoholic beverages. The results indicated that any driving during this hour is hazardous, not just at intersections with flashing signals.

The first Michigan study (7, 8) found similar results. The hour immediately following the closing of night clubs had a significantly higher rate of right-angle accidents at intersections with flashing signal operation as compared to intersections with normal signal operation.

Driver Comprehension of Flashing Operation

In the absence of vehicles on the cross-street, a driver facing a flashing red indication cannot tell whether the cross-street has a flashing red or flashing yellow indication. If the driver assumes that the cross-street is approaching a flashing red, when in fact it is a flashing yellow signal, then the driver may enter the intersection in the direct path of an approaching vehicle.

Driver comprehension of flashing signal indications was tested in the FHWA study on signal operations (6) and a TTI study on comprehension of traffic control devices (13). In both studies, drivers had a very high understanding of the meaning of the flashing indication they were facing. But their level of understanding significantly decreased when they were asked what indication the intersecting traffic would see. Table 2-11 summarizes the findings of these two studies for a driver facing a flashing red indication. These responses show that use of the yellow/red flashing mode creates a predicament for the traffic engineer. While yellow/red flash results in less delay than red/red flashing, it also presents a greater potential for driver misunderstanding than red/red flashing.

Table 2-11. Driver Comprehension of Flashing Indications

Question: If you are facing a flashing red signal, what will the cross-street traffic do?

Response	**FHWA Study (6)**	**TTI Study (13)**
Slow	39.4%	13.8%
Stop	27.8%	41.0%
Cannot Tell	32.9%	41.1%
Not Sure	---	4.1%
No. of Respondents	353	1,745

Modes of Flashing Operation

The color indications used for flashing signal operation can be either yellow/red or red/red. Yellow/red flashing operation displays a flashing yellow to the major street and a flashing red to the minor street. Red/red flashes red to both streets. The MUTCD specifically states that flashing yellow shall not be displayed to both streets. Only the FHWA report (6) and the MUTCD (1) contain information referencing when to use the red/red or yellow/red color combination. The FHWA study (6) recommended that red/red flashing operation should not be used as an alternative to normal signal operation during early morning, low-volume periods. The MUTCD does not mention the use of red/red flashing operation.

Delay/Stops and Flashing Operation

Operating signals in the yellow/red flashing mode during low-volume nighttime conditions can significantly reduce delay to motorists on the major street. However, of the previous research studies evaluated for this literature review, only the FHWA study (6) explicitly considered and quantified the delay savings resulting from flashing operation.

In the FHWA study, mean delay and proportion of vehicles stopping were calculated for the major and minor streets controlled in the following manners: flashing yellow/red, flashing red/red, pretimed isolated, pretimed arterial, pretimed network, fully actuated, semi-actuated isolated, and semi-actuated with background cycle. The study found that total delay depends on the street volumes, but generally found that flashing yellow/red operation produces less delay than all other forms of control. It also found that flashing red/red operation produces only slightly less delay than regular operation of signals in a well-timed arterial or network system, and produces more delay than actuated signals. With regards to stops, the FHWA study found:

- Flashing yellow/red operation produces fewer stops than pretimed operation when the volume ratio is above 1.1 for isolated signals, above 2.5 for arterial systems, and above 3.0 for network systems.
- Flashing yellow/red operation produces fewer stops than actuated control under all combinations of volumes.
- Flashing red/red operation produces more stops than any form of normal operation under all volume conditions.

Table 2-12 indicates the delay and stops determined in the FHWA study. Chapter 4 of this report contains more detailed information about the delay associated with flashing operation and the manner in which the FHWA study determined delay for flashing operation.

Table 2-12. Delay and Stops from FHWA Study (6)

Control Strategy	Mean Delay (sec/veh)		Proportion Stopping		Source of Data
	Major St	Minor St	Major St	Minor St	
Flashing Yellow/Red	0.1	3.7	0.000	1.000	Field Studies
Flashing Red/Red	2.7	4.0	1.000	1.000	Field Studies
Pretimed, Isolated	5.0	18.0	0.330	0.650	Previous Research (14)
Pretimed, Arterial	2.7	8.1	0.200	0.501	Field Studies
Pretimed, Network	2.7	5.0	0.200	0.387	Field Studies
Fully Actuated	1.4	5.2	0.076	0.997	Field Studies
Semi-Actuated, Isolated	0.39	5.46	0.090	0.997	Analytical Model
Semi-Actuated, Background Cycle	0.23	26.97	0.057	0.998	Analytical Model

Flashing of Malfunctioning Traffic Signals

Besides flashing during low-volume nighttime periods, a traffic signal may begin flashing operation when there is a malfunction in the signal operation. Typical malfunctions include controller failure, loadswitch failure, and voltage transients, sags, and outages. Known as emergency or conflict flashing, this type of flashing operation is not uncommon, but it occurs randomly and cannot be predicted. Only one study (15) has looked at the impact of emergency flashing. The study included a review of pertinent documents, evaluation of intersection sight distance at several intersections, and interviews with local traffic engineers.

One of the key findings of this study is that sufficient sight distance must be provided on the minor street when yellow/red flashing is used. The study recommended that AASHTO Case III intersection sight distance (16) be used for flashing operation. Local traffic engineers stated that red/red flashing is too harmful to major street traffic, even if there are not enough gaps with yellow/red flashing to allow the vehicles on the minor street to enter the intersection. Using red/red flash will cause significant delays on the major street and may prevent a timely response by police, emergency vehicles, or signal technicians.

Discussion of Previous Research Findings

This review of previous research on flashing signal operation found that accidents are the most often evaluated aspect of nighttime flashing signal operation. Other factors, such as delay and energy savings, while considered in some studies, have not been widely evaluated. A difficulty associated with evaluating the accuracy of the study findings is the manner in which the studies were performed. The manner of analysis and the factors considered are not consistent in all studies. The differences between the studies is especially critical when making comparisons between study findings. A good example of this problem is the use of the volume ratio. One study specifically defined the volume ratio of major street ADT to minor street ADT (5). A second study defined the volume ratio on the basis of hourly volume (7, 8), while a third study uses the volume ratio but does not indicate what volumes it represents (10). The ability to generalize the findings of these studies to specific conditions is also limited in some cases by the conditions under which the studies were performed. In the Portland study, for example, 22 of the 30 intersections had a major street speed limit of less than 30 mph (50 km/h) and only eight intersections had a major street speed limit over 30 mph (50 km/h). Therefore, it may be questionable whether the results of this study can be applied to major streets with a 40 mph (65 km/h) speed limit.

Accidents

The many studies that have evaluated the accident impacts of flashing signal operation have generally determined that accidents are higher with nighttime flashing operation than with 24-hour normal operation. However, a closer inspection reveals that several of these studies are based on the analysis of accidents at a limited number of intersections or for a limited period of time. For instance, the conclusions of the first of the Oakland County, Michigan studies (7, 8) are based on the analysis of accidents at six intersections, and the findings of the Washington, D.C. study (3) are based on five months of before-and-after data. As a result, it is not surprising to find that some of the more specific conclusions about accidents and flashing operation conflict with one another. As an example, the first Michigan study (7, 8) concluded that the accident rate with flashing operation is higher when the volume ratio is less than two, while the Portland study (10) recommended that flashing operation be used when the volume ratio is less than two.

Table 2-13 summarizes the types of accident analysis that were done for each study and the parameters that were considered in the analysis. Table 2-14 compares some of the accident frequencies and/or rates for flashing operation that were identified in several of the studies. Table 2-14 indicates that there is a wide range in accident frequencies and rates for the various studies. Based on the information shown in Table 2-14, it appears that the expected accident rate for a given intersection, whether in flash or normal operation, is difficult to ascertain. Therefore, while the generalization can be made that there may be a higher incidence of accidents with flashing operation than with normal operation, the actual relationship between the two operating conditions may depend more on the individual intersection than on any other factor. The Los Angeles County study (4) indicated that the accident rate for flashing operation is related to the accident rate during normal operation and that intersections with low accident rates during normal operation will likely have a low rate during flashing operation. Several of the studies also indicate that there may be a relatively small number of accidents at an intersection with flashing operation. As the number of accidents at an intersection gets smaller and smaller, the random nature of accidents makes it increasingly difficult to identify trends in the accident data.

Table 2-13. Summary of Previous Flashing Signal Accident Studies

Study		Oregon	Michigan	Michigan	FHWA S.F.	FHWA non-SF	Marson's Thesis	L.A.	D.C.
Year		1984	1987	1983	1980	1980	1976	1972	1966
Reference Number		(10)	(9)	(7, 8)	(6)	(6)	(5)	(4)	(3)
Type		B&A	B&A	B&A	B&A	B&A	W&WO	B&A	B&A
No. of Intersections		30	59	6	520	58	169	18	741
No. of Intersection for Type of Signal Change	Y/R to N	30	59	6			99	16	162
	R/R to N							2	
	Y/R to R/R				2				
	Y/R to Y/R								579
	N to N				107		70		
	N to Y/R				375	58			
	N to R/R				36				
Data Period	Before/With	1-2 yr	4 yr	3 yr	variable	3 yr	variable	1 yr	5 mo
	After/Without	1-2 yr	1 yr	3 yr	variable	1 yr	variable	1 yr	5 mo
Accident Statistic	Frequency		✓			✓		✓	✓
	Rate	✓		✓	✓	✓	✓		
Total Accidents		✓	✓		✓	✓	✓	✓	✓
Accident Severity	Fatality				✓	✓			
	Injury	✓			✓	✓		✓	
	PDO	✓			✓	✓	✓		
Accident Type	Angle	✓	✓	✓	✓	✓	✓		✓
	Rear-End	✓	✓		✓	✓	✓		✓
Intersection Factors	Volume Ratio	✓		✓		✓	✓		
	Int Type	✓			✓	✓	✓		
	Int Angle						✓		
	Speed	✓				✓	✓		
	Time			✓	✓				

Table 2-14. Comparison of Accident Analysis Results

Study	Reference	No. of Intersections	Condition	Accident Frequency[1]		Accident Rate[2]	
				Total	Angle	Total	Angle
Washington D.C.	(3)	162	Flash	0.95	0.52	---	---
			Normal	0.61	0.22	---	---
FHWA San Francisco	(6)	375	Flash	0.48	0.40	---	---
			Normal	0.18	0.13	---	---
FHWA National	(6)	55/58[3]	Flash	2.72	1.02	4.44	2.34
			Normal	1.24	0.26	2.66	0.64
Los Angeles	(4)	18	Flash	2.11	1.83	---	---
			Normal	1.00	0.33	---	---
Oakland Co., Michigan	(7, 8)	6	Flash	---	---	---	81.52
			Normal	---	---	---	1.82
Oakland Co., Michigan	(9)	59	Flash	---	0.86	---	---
			Normal	---	0.08	---	---
Marson's Thesis	(5)	99	Flash	---	---	2.78	1.16
		70	Normal	---	---	2.42	0.61
Portland, Oregon[4] Speed Limit < 30	(10)	22	Flash	---	---	3.36	0.77
			Normal	---	---	1.61	2.56
Portland, Oregon[4] Speed Limit > 30	(10)	8	Flash	---	---	4.18	2.59
			Normal	---	---	2.16	0.16

Notes: Table comparing nighttime yellow/red flash to 24-hour normal operation.

Accident rates and frequencies are for flashing operation or equivalent periods of normal operation.

[1] Accidents per intersection per year.

[2] Accidents per million entering vehicles.

[3] 55 intersections used for determining the rate and 58 intersections used determining the frequency.

[4] Results of Oregon accident analysis were not provided for all intersections.

Volume Ratio

There are four studies (FHWA (6), Marson's thesis (5), Oakland County (7, 8), and Portland (10)) which specifically address the relationship between the volume ratio and accidents. However, as mentioned previously, the volume ratio was not measured in the same manner in all four studies. Table 2-15 compares accident rates for various volume ratios from three of the studies. The description of the Oakland County analysis does not include the accident statistics related to the volume ratio. The Oakland County study concluded that angle accidents are more common at flashing intersections when the volume ratio is two or less than when the ratio is four or more, but it gave no data to support this statement. As was the case with the general accident statistics, Table 2-15 shows some significant variability in the accident rates for the various volume ratios. In fact, the findings do not agree in all cases, leading different studies to develop conflicting conclusions. The Portland study concluded that flashing operation is safer when the volume ratio is less than two, while the FHWA and Oakland County studies concluded that flashing operation is safer when the volume ratio is greater than four. Because of the variability in the accident rates, the limited number of intersections used in the analysis, and the conflicting conclusions of some of the studies, the findings of previous studies related to volume ratio must be used with caution.

Volumes

The impact of traffic volume on flashing operations was addressed in the FHWA (6) and Oakland County (7, 8) studies. The FHWA study concluded that flashing operation can be used when the major street volume is less than 200 vph. The Oakland County study concluded that traffic volume did not impact accident rates, but it did not provide specific data in the study descriptions to support its conclusions. However, the FHWA analysis is based on accident data for a limited number of intersections within each volume category. Therefore, their conclusions must be used with caution, particularly since the FHWA study is the only one to analyze the impact of volume and provide data to support its conclusions.

Table 2-15. Comparison of Volume Ratio and Accident Rate

Type of Accident	Condition	Study	Volume Ratio (FHWA Study (6))						
			<1	>1 & ≤2	>2 & ≤3	>3 & ≤4	>4 & ≤5	>5 & ≤10	>10
			Volume Ratio (Marson's Thesis (5) and Portland (10) Studies)						
				≤2		>2 & ≤4		>4	
Total	Flash	FHWA	6.45	5.99	2.86	1.69	4.20	0.94	2.12
		Marson's Thesis		2.91		3.20		2.22	
		Portland		1.06		5.44		2.76	
	Normal	FHWA	5.11	3.62	0.57	1.90	1.36	2.20	0.40
		Marson's Thesis		2.36		2.21		3.31	
		Portland		3.29		1.20		1.89	
Angle	Flash	FHWA	2.79	4.06	2.17	0.85	2.51	0.23	0.27
		Marson's Thesis		1.33		1.46		0.71	
		Portland				3.30		2.21	
	Normal	FHWA	0.91	1.45	0.00	0.63	0.00	0.33	0.21
		Marson's Thesis		0.73		0.45		0.50	
		Portland				0.00		0.43	
No of Intersections		FHWA	5	10	12	4	5	8	9
		Marson's Thesis		21/36[1]		42/23[1]		36/8[1]	
		Portland		4		14		12	

Note: [1] Number of intersections with flashing operation/number of intersections with normal operation.

Environmental Impacts

There are three ways that flashing signal operation can have a positive impact on the environment: reduced fuel consumption, reduced vehicle emissions, and reduced electrical power consumption. Only the FHWA study (6) has looked at the environmental impacts of flashing signal operation with any detail. The total fuel savings estimate in the FHWA study is based on some very rough approximations about the use of flashing signals in the United States and the volumes that would be present at flashing intersections. Therefore, the total fuel savings estimate of this study may or may not be accurate. The fuel emissions impact of flashing operation is not described in sufficient detail to verify or disprove the findings. The FHWA study did not measure the electrical power savings of flashing signals. Instead, it used power consumption findings of a different study to determine the differences between normal and flashing operation. As a result of these factors, the information in the FHWA report cannot be used to accurately ascertain the environmental impacts of flashing operation.

Driver Comprehension

Two studies (6, 13) have looked at how well drivers understand a flashing traffic signal. Both studies show that drivers have a good understanding of the meaning of a flashing yellow or flashing red indication. However, both studies also show that drivers lack a fundamental understanding of the indication displayed to cross-street traffic. This finding may help to explain why flashing operation may lead to more accidents. A driver approaching a flashing red indication will stop at the intersection. However, at low volumes, there are few vehicles on the cross-street to tell the driver whether cross-street traffic is facing a flashing red or flashing yellow. If the driver assumes cross-street traffic has a flashing red, when in fact it is a flashing yellow, the driver may pull into the intersection in front of an oncoming vehicle, causing an accident.

Conclusions from Literature Review

Flashing operation of traffic signals has been widely used over the years as an alternative to operating signals in the normal mode (green-yellow-red) at all times. Despite this fact, there are no comprehensive guidelines for the operation of flashing signals, nor is there an abundance of information about the impacts of flashing signal operation. Most of the evaluations about flashing signal operation have focused on the relationship between flashing operation and accidents. These studies have attempted to establish a relationship between accidents at flashing intersections and some other measurable factors, such as traffic volume, volume ratio, and time of night. Other factors which have been considered include a reduction in delay, energy conservation, and driver comprehension of flashing signal indications.

The most comprehensive evaluation of flashing signal operation was performed as part of an FHWA study (6). The FHWA study evaluated flashing operation from the standpoint of accident, traffic volume, volume ratio, delay, and energy conservation. Other studies of flashing operation have typically evaluated the accident impacts of flashing operation. Many of these studies have used data from a limited number of intersections or a limited time period. The review of reference documents and results of previous research have led to the following conclusions about flashing signal operation:

- The use of flashing operation during low-volume conditions has the potential to reduce stops and delay for major street traffic and reduce delay to minor street traffic. This in turn can result in reduced fuel consumption and reduced fuel emissions.
- Flashing operation will reduce electrical consumption of the traffic signal.
- Accidents during flashing operation appear to be more numerous than accidents during normal operation. In particular, right-angle accidents seem higher with flashing operation than with normal operation.
- Several studies have identified a relationship between the volume ratio and accident rates at intersections with flashing operation. However, the threshold value for the volume ratio varies between studies. The literature review identified the following volume ratio thresholds at which flashing operation reduces the likelihood of accidents:
  - Volume ratio of three or more.
  - Volume ratio of four or more.
  - Volume ratio of two or less.
- The relationship between volume and accidents at intersections with flashing operation is uncertain. The following relationships were found in different studies:
  - Flashing operation appears to be safer when the two-way volume on the major street is less than 200 vph.
  - There is no relationship between accidents and volume.

- The volumes used as the basis for the volume ratio vary between studies.
- Yellow/red flashing operation should not be used if the following accident levels are reached or exceeded at an intersection:
    - Three right-angle accidents in one year during flashing operation (short-term rate).
    - Two right-angle accidents per million vehicles during flashing operation, if the rate is based on an average of three to six observed right-angle accidents per year (long-term rate), or
    - 1.6 right-angle accidents per million vehicles during flashing operation, if the rate is based on an average of six or more right-angle accidents per year (long-term rate).
- If the accident rate is low with normal operation, it will remain low with flashing operation.
- Accidents at intersections with flashing operation are more common in the hour following the time that nightclubs close.
- Drivers facing a flashing red indication do not appear to understand that the conflicting traffic may be facing a flashing yellow or a flashing red indication.
- Red/red flashing is a safer mode because all vehicles must stop.
- Yellow/red flashing is the more efficient mode because major street vehicles are not required to stop.
- The delays and congestion which can result from red/red flashing may be undesirable during daytime hours.
- Congestion resulting from red/red flash may delay the arrival of police, ambulance, or signal technicians during some portions of the day.
- Yellow/red flashing produces less delay than all other forms of signal control.
- Some of the findings of previous studies are based on data from a limited number of intersections or for a limited period of time.

CHAPTER 3
REVIEW OF CURRENT PRACTICE

As shown in the previous chapter, there is a wide variety of factors which need to be considered in making a decision to implement flashing operation of traffic signals. This variety of factors, combined with a lack of usable guidelines, force most traffic engineers to make decisions related to flashing operation on the basis of engineering judgement or field experience. In order to characterize this decision-making process, information was collected to identify current flashing signal practices, including existing guidelines for flashing signal operation. The information was obtained through two surveys of flashing signal practices, a review of previous surveys on flashing signal operation, a review of the MUTCD guidelines, and contacts with transportation professionals.

TTI Survey of Flashing Practices in Texas

One of the first efforts in the study was to conduct a survey of flashing practices in TxDOT districts and local Texas agencies. The survey provided the opportunity to gather information about many different aspects of flashing operation and to assist in the data collection efforts of the study. Recognizing these opportunities, the following objectives were established for the survey of flashing signal operation:

1. Identify where and how flashing operation is currently utilized on a regular basis in TxDOT districts and Texas cities.
2. Determine the guidelines or warrants that the districts or local agencies use to implement flashing signal operation.
3. Determine if any programs have been established to monitor the impacts of flashing operation.
4. Identify potential study site locations for the research study.

The survey was developed in a manner that it could be sent to a large number of districts and agencies and could be quickly answered by the traffic engineering personnel at the various agencies. The number of questions was limited to ten, and most of them were phrased as multiple choice questions. The ten questions are shown in Table 3-1. The cover letter and survey instrument are reproduced in Appendix A.

Table 3-1. Questions in Texas Practices Survey

Number	Question
1	Are there any signalized intersections within your jurisdiction which use flashing operation on a regular (or normal) basis?
2	Under what conditions does your district or agency place traffic signals in flashing operation?
3	Please indicate any factors which are addressed in your district or agency guidelines for flashing operation, if you have such guidelines.
4	Would guidelines for flashing signal operation be useful to your agency?
5	If you use normal flashing operation, can TTI study flashing operation at one or more of these intersections?
6	Do you use flashing operation with actuated controllers?
7	Have you ever performed an analysis of the effectiveness of flashing operation?
8	Would you be willing to implement flashing operation within your jurisdiction on an experimental basis using the preliminary guidelines developed in this research?
9	On what basis do you select the color indications (yellow/red or red/red) for flashing operations?
10	Please make any suggestions about aspects of flashing signal operation which you think should be studied.

The survey was intended to provide insight into both TxDOT and local flashing practices; therefore, the survey was sent to personnel from both types of agencies. Surveys sent to TxDOT districts were typically sent to the District Traffic Engineer, District Signal Shop Supervisor, and/or District Maintenance Engineer. In most cases, surveys were sent to two or three individuals in each district. Multiple responses from a single district were consolidated into one survey response so that each district is represented by one survey. Surveys were also sent to traffic engineers in a number of local transportation departments in Texas in order to ascertain flashing signal practices at the local level. Local information was sought due to the need for consistency in developing and implementing guidelines for flashing operations. The agencies which responded to the survey are shown in Tables 3-2 and 3-3.

Table 3-2. TxDOT Districts Responding to Survey of Texas Practices

No.	City	No.	City	No.	City
1	Paris	9	Waco	17	Bryan
2	Fort Worth	10	Tyler	18	Dallas
3	Wichita Falls	11	Lufkin	19	Atlanta
4	Amarillo	12	Houston	20	Beaumont
5	Lubbock	13	Yoakum	21	Pharr
6	Odessa	14	Austin	23	Brownwood
7	San Angelo	15	San Antonio	24	El Paso
8	Abilene	16	Corpus Christi	25	Childress

Table 3-3. Local Agencies Responding to Survey of Texas Practices

Cities			Counties
Abilene	Dallas	Lubbock	Dallas County
Amarillo	El Paso	Midland	
Arlington	Fort Worth	Pasadena	
Austin	Garland	Richardson	
Baytown	Houston	San Antonio	
Beaumont	Irving	Tyler	
Brownwood	Laredo	Waco	
Carrollton			

The survey responses were analyzed in a number of different ways in order to obtain comprehensive insight into flashing signal operation in Texas. The raw response rates and percentages are shown in Appendix B. Not only does Appendix B give the total response percentages for each question, it also divides the response rates between the TxDOT districts and local agencies. The responses and issues related to the individual questions are discussed in the following subsections.

It should be noted that the answers to several of the questions do not indicate the extent to which flashing is used within any given agency's jurisdiction. For example, eight respondents indicated that they use flashing operation in school areas. However, there may be only one location within each of the eight jurisdictions where a signal is flashing in a school area.

Uses of Flashing Operation (Question 1)

The first question of the survey asked "Are there any signalized intersections within your jurisdiction which use flashing operation on a regular (or normal) basis?" This question was asked to determine the extent to which flashing guidelines would be applicable. Normal or regular flashing operation includes all types of flashing other than emergency or railroad preemption flashing. This question was intended to identify the extent to which flashing operation is used in Texas. Responses percentages to this question are summarized in Table 3-4. Responses to this question indicated that 67 percent of TxDOT districts and 74 percent of local agencies used flashing operation on a regular basis. These responses confirmed the wide use of flashing operation and the need to investigate its use.

Table 3-4. Responses to Question 1

Are there any signalized intersections within your jurisdiction which use flashing operation on a regular (or normal) basis?			
Response	**TxDOT Rate (%)**	**Local Rate (%)**	**Total Rate (%)**
Yes	66.7	73.9	70.2
No	33.3	26.1	29.8

Conditions for Flashing Operation (Question 2)

The second question asked respondents to identify "Under what conditions does your district or agency place traffic signals in flashing operation?" A list of seven choices was provided so that the respondent could check those conditions which applied. An eighth choice of "Other" was also provided. This question was asked in order to identify how flashing operation is used in various areas. Responses and the relative rankings for this question are shown in Table 3-5.

Table 3-5. Responses to Question 2

Under what conditions does your district or agency place traffic signals in flashing operation?

Response	TxDOT		Local		Total	
	Rank	Rate (%)	Rank	Rate (%)	Rank	Rate (%)
Emergency (due to failure)	1	95.8	1	95.7	1	95.7
Signal installation/removal	2	75.0	3	60.9	2	68.1
Early morning hours	4	58.3	2	73.9	3	66.0
Railroad preemption	3	70.8	4	39.1	4	55.3
Other low-volume periods	5T	12.5	5	30.4	5	21.3
Other	5T	12.5	6T	26.1	6	19.1
School areas	7	8.3	6T	26.1	7	17.0
Do not place signals in flash	8	4.2	8	0	8	2.1

Some of the "Other" conditions under which flashing operation is used include the following:

- During construction or maintenance activities.
- While testing equipment performance.
- During periods of inclement weather (typically with snow and ice).
- At entrances to shopping centers.
- At entrances to fire stations.
- For major or special events.

The flashing conditions can be divided into regular and variable flashing operation, in the same way described for Question 1. Variable flashing operation occurs on a random basis and cannot be predicted. Among the choices given in Question 2, emergency and railroad flashing are classified as variable. Four choices are classified as regular flashing, or flashing which occurs on a predictable basis. These choices include during early morning hours, during low-volume periods other than early morning hours, in school areas, and for signal installation/removal.

Among the variable flashing operation, flashing in an emergency related to signal failure is used by virtually every one of the respondents (97 percent). Railroad preemption flashing is also commonly used. There was a fairly significant difference between the districts and the local agencies in the use of flashing with railroad preemption. However, this difference seems logical when one considers that railroad preemption in urban areas probably displays a green indication to the non-conflicting movement.

Among the choices for regular flashing operation, early morning flashing or signal installation/removal flashing were the two most common uses, with both being used by approximately two-thirds of the respondents. Flashing during early morning hours was more common among the local agencies (74 percent) than the TxDOT districts (58 percent), and flashing for signal installation/removal was more common with the districts (75 percent) than with the local agencies (61 percent). These results compare closely to a similar question from the survey given as part of the FHWA study on signal operations (6). In that question, 63.4 percent stated that they used flashing operation during low-volume periods.

Two other conditions for which flashing is not commonly used are during low-volume periods other than early-morning hours and in school areas. In both situations, the local agencies use flash more than the districts (30 percent versus 13 percent for low-volume periods and 26 percent versus 8 percent for school areas). Additionally, while some respondents indicated that they use flashing in school areas, there may be only one or two locations where school area flashing is used within that jurisdiction.

It is interesting to note that of all the districts and local agencies (47 total), only one district does not place signals in flashing operation. A number of respondents (three districts and six local agencies) also indicated other uses for flashing operation. These include flashing in construction or maintenance areas (two local agencies), during testing of equipment (one district), during inclement weather (one district and one local agency), at entrances to shopping centers and fire stations (one district and two local agencies), and for special events (one local agency).

Factors Included in Flashing Guidelines (Question 3)

The third question asked the respondents to "... indicate any factors which are addressed in your district or agency guidelines for flashing operation, if you have such guidelines." This question was asked in order to identify the most common basis for deciding to implement flashing operation. About half of the survey respondents checked one or more of the factors upon which their guidelines are based. Therefore, the response percentages add up to more than 100 percent. Table 3-6 shows the percentage of survey respondents in each category who checked each factor and the relative ranking of each factor.

Table 3-6. Responses to Question 3

Please indicate any factors which are addressed in your district or agency guidelines for flashing operation, if you have such guidelines.

Factor	TxDOT		Local		Total	
	Rank	Rate (%)	Rank	Rate (%)	Rank	Rate (%)
Traffic Volume	1	43.5	1	56.5	1	48.9
Time of Day	2	33.3	2	47.8	2	40.4
Accidents	4	16.7	3	30.4	3	23.4
Other	3	25.0	8	13.0	4	19.1
Day of Week	6	8.3	4T	26.1	5	17.0
Relation to Other Intersections	5	12.5	6T	17.4	6	14.9
Geometrics	7T	4.2	4T	26.1	7	14.9
Posted Speeds	7T	4.2	6T	17.4	8	10.6
No Guidelines	*	45.8	*	47.8	*	46.8

* Not ranked as a factor

Almost half (47 percent) of all the respondents indicated that they do not have any guidelines for implementing flashing operation. The district and local agency response percentages to this choice were almost identical. The response to this choice indicates the potential usefulness of guidelines for flashing signal operation. For the most part, if a respondent checked "no guidelines" to Question 3, then no other factors were checked. However, in a few cases, respondents checked "no guidelines" and added the note "written" next to it. They then checked one or more of the other factors and added the note "engineering judgement" next to those. A similar question was asked in the FHWA survey on signal operations (6). In that question, 56.9 percent stated they did not have any warrants for setting signals in flashing operation.

In general, the relative rankings of the factors are consistent between TxDOT districts and local agencies, with the exception of the "Other" factor. The TxDOT districts consider other factors much more often than the local agencies. Among the specific factors listed in the survey, traffic volume, time of day, and accidents are considered the most when deciding whether to flash signals. All three factors have rates greater than 20 percent, except for TxDOT consideration of accidents, which was selected by only 17 percent of TxDOT respondents.

The other four factors -- day of the week, relation to other intersections, geometrics, and posted speeds -- were considered more often by the local agencies than they were by TxDOT districts. Day of the week, geometrics, and posted speeds were considered by a very limited number of TxDOT districts. All of these were selected by less than 10 percent of the districts. The fourth factor -- relation to other intersections -- was selected by less than 15 percent of the districts. In contrast, these four factors were each selected by at least 15 percent of the local agencies, indicating that the local agencies are more likely to consider a larger number of factors when making a decision about flashing operation. Some of the "Other" factors identified in the surveys include the following:

- Local agency input.
- Weather effects.
- Texas MUTCD.
- Type of signal operation.
- Each intersection is considered individually.

Usefulness of Flashing Guidelines (Question 4)

The fourth question asked "Would guidelines for flashing signal operation be useful to your agency?" The possible choices included "Yes," "No," and "Maybe." This question was asked to determine the interest and potential usefulness of guidelines developed from the research activities. Responses to this question are shown in Table 3-7.

The responses indicate that only a very small percentage would not consider the use of any guidelines developed from this study. A little more than half of the respondents think they would use the guidelines and about a third indicated cautious interest in the guidelines.

Table 3-7. Responses to Question 4

Would guidelines for flashing signal operation be useful to your agency?			
Response	**TxDOT Rate (%)**	**Local Rate (%)**	**Total Rate (%)**
Yes	45.8	69.6	57.4
No	12.5	4.3	8.5
Maybe	37.5	26.1	31.9

Potential Study Sites (Question 5)

The fifth question asked if the research team could collect data at any flashing signal intersections within that district's or agency's jurisdiction. This question was asked to help the research team identify locations where they could collect data for this study. The responses to this question are shown in Table 3-8.

Table 3-8. Responses to Question 5

If you use normal flashing operation, can TTI study flashing operation at one or more of these intersections?			
Response	**TxDOT Rate (%)**	**Local Rate (%)**	**Total Rate (%)**
Yes	50.0	73.9	61.7
No	37.5*	21.7*	16.3*
Maybe	12.5	4.3	8.2

* All of those that responded "No" do not flash signals on a regular basis.

Flashing with Actuated Controllers (Question 6)

The sixth question asked districts and local agencies "Do you use flashing operation with actuated controllers?" Space was given at the end of the question for comments. This question was added to the survey because of conflicting opinions about whether flashing operation is appropriate at actuated intersections. Intuitively, it would seem that flashing operation would not be needed at an actuated intersection due to the ability of an actuated signal to respond to the demands of traffic. However, the responses to this question indicate that there is much greater use of flashing with actuated controllers than originally thought. Table 3-9 shows the responses to this question.

Table 3-9. **Responses to Question 6**

Do you use flashing operation with actuated controllers?			
Response	**TxDOT Rate (%)**	**Local Rate (%)**	**Total Rate (%)**
Yes	37.5	56.5	46.8
No	45.8	30.4	38.3
Maybe	16.7	4.3	10.6

This is the only question where there was a large difference between the districts and the local agencies. Among the TxDOT districts, there were more that do not use flashing with actuated controllers than there were that do. Among the local agencies, more do use flashing with actuated controllers than do not.

One possible explanation for the large number of agencies which use flashing with actuated control is that the flashing operation might be limited to certain applications resulting from emergency, conflict, maintenance, preemption, and installation/repair. However, conversations with some of the survey respondents indicate that flashing an actuated signal during low-volume periods is not unusual.

This question generated more comments than any other multiple choice question. The comments indicated some of the situations in which actuated signals are flashed. These situations include:

- At railroad crossings for preemption.
- In response to a conflict (emergency flash).
- During maintenance or testing activities.
- During installation or removal of an actuated signal.
- When the signal is part of a coordinated system experiencing low volumes.

While not a part of the survey, several individuals were asked about operation of an actuated signal during low volume periods. Their responses indicated that the following timing alternatives are commonly used:

- Soft Recall - In this alternative, the signal rests in green on the major street until a call is made by a vehicle on the minor street. This alternative appears to cause the least delay on major street traffic.
- Rest in Last Green - In this alternative, the signal remains in green on the last street to receive a green indication. This alternative assumes that the probability is highest that a vehicle will follow an earlier vehicle on the same street.
- Rest in Red - In this alternative, the signal displays a red indication to all approaches until a vehicle arrives and calls a green. This alternative is effective at controlling speeds because it causes vehicles to slow as they approach the intersection. Also, because an all-red display is shown, there is no need for a clearance interval, and a green can be displayed immediately after a call is placed.

The FHWA study (6) on signal operations asked a similar question in their survey. Of the agencies that use flashing operation during low-volume periods, 42.9 percent used flashing operation at semi- or full-actuated isolated intersections.

Evaluation of Flashing Operation (Question 7)

The seventh question asked if the districts or local agencies had "...ever performed an analysis of the effectiveness of flashing operation?" This question was asked to help the research team identify previous research efforts which were similar or related to this study. The results of an analysis performed by a district or local agency are rarely published, and therefore, they are sometimes difficult to identify and obtain. It was also hoped that the results of other analysis would indicate some of the most important measures of effectiveness. Responses to this question are shown in Table 3-10.

Table 3-10. Responses to Question 7

Have you ever performed an analysis of the effectiveness of flashing operation?			
Response	**TxDOT Rate (%)**	**Local Rate (%)**	**Total Rate (%)**
Yes	0.0	17.4	8.5
No	100.0	82.6	91.5

As Table 3-10 indicates, no TxDOT districts and only four local agencies have analyzed the effectiveness of flashing operation. A similar survey question was also asked in the FHWA study on signal operations (6). The question found that 79.3 percent of the responding agencies had not studied the effects of flashing operation on traffic operations or accidents.

Flashing Experimentation (Question 8)

The eighth question asked the survey participants "Would you be willing to implement flashing operation within your jurisdiction on an experimental basis using the preliminary guidelines developed in this research?" This question was added to the survey to accelerate progress in the second year of the research study. The results to this question are shown in Table 3-11. The responses indicate that there is cautious interest in experimenting with the guidelines and very little opposition to the development of such guidelines.

Table 3-11. Responses to Question 8

Would you be willing to implement flashing operation within your jurisdiction on an experimental basis using the preliminary guidelines developed in this research?

Response	TxDOT Rate (%)	Local Rate (%)	Total Rate (%)
Yes	33.3	39.1	36.2
No	12.5	4.3	8.8
Maybe	54.2	56.5	57.8

Flashing Mode (Question 9)

The ninth question asked "On what basis do you select the color indications (yellow/red or red/red) for flashing operations? This question was asked to help the research team identify practices related to the second objective of the study, that is, the color of flashing indications. This is one of two questions which were not multiple choice questions. Some of the most common responses to this question include:

- Traffic volumes or volume ratio - yellow on major street and red on minor street.
- Normal flash is yellow/red; conflict or emergency flash is red/red.

- Confusion with yellow/red flashing operation is leading to use of red/red flashing operation at all locations.
- Consistency with other signals.
- Red/red flashing operation if volumes are nearly equal.
- Speeds.
- Default flash - red/red, time of day flash on high speed roadway - yellow/red, time of day flash on low speed rural roadway - red/red.
- Geometrics.
- Accident history.
- Red/red flashing operation used at all times.
- Red/red flashing operation at locations with sight distance restrictions or accident history.
- Red/red flashing operation for diamond interchanges.
- Based on arrangement of STOP signs prior to signal installation.
- Police input.
- Red/red flashing operation is not used in order to eliminate driver confusion.

Suggestions for Further Study (Question 10)

The tenth question asked respondents to "... make any suggestions about aspects of flashing signal operation which you think should be studied." This question was asked in order to identify additional aspects of flashing operation which are of concern to traffic engineers and to insure that this research study is as complete as possible. This was the second question which was not multiple choice. Some of the most common responses include:

- Impacts of yellow/red flashing operation and red/red flashing operation at the same intersection during different times of the day.
- Flashing of signals in school area where normal signal operation is necessary only two or three times a day.
- Effects on drivers of the change from normal operation to flashing operation.
- Flashing at a diamond interchange that does not meet signal warrants and has an accident history.
- Treatment of left-turns during flashing operation.
- Behavior of large trucks at red/red flash in rural areas.

- Effectiveness of flashing actuated signals.
- Liability during flash.
- Driver respect of a signal which is in normal operation only during a few high-volume hours a day.
- Changing flashing mode at a given intersection leads to serious accidents.
- Method of telling the driver the flashing indication of the cross-street.
- Use of red/red flashing operation at actuated signals during low volumes.
- Effect of population on flashing operation.
- Color indications for beginning and ending flashing operation.
- Traffic volumes at which flashing becomes more efficient in terms of vehicle stops, not delay.
- Impacts of pedestrians on flashing operation.
- Fuel savings resulting from flashing operation.
- Impacts of flashing operation on accidents.

Summary of TTI Survey of Flashing Practices in Texas

The survey of Texas flashing practices provided some useful insight into how the various TxDOT districts and local agencies actually use flashing signal operation. For most of the questions, the TxDOT districts and local agencies responses were similar. Most of the differences in responses can be attributed to the differences between the use of traffic signals in urban and rural areas.

The survey indicated that flashing operation is widely used in Texas, although it is used in different manners across the state. There are no widely used guidelines for flashing operation, although the decision to implement flashing operation is usually based on the same basic factors: volumes, accidents, and time-of-day. There is also wide variation in the basis used to select the flashing mode (yellow/red or red/red). Contrary to expectations, flashing operation with actuated controllers is not uncommon. Few of the respondents have evaluated the effectiveness of flashing operation, and most of the respondents are interested in the development of guidelines for flashing signal operation. The survey findings tend to support the following statement which is found in a recent book on traffic signals (17):

> *"A number of warrants have been developed for determining when to place a signal into flashing operation. The reality however, it that very few jurisdictions have the time to evaluate such criteria and the decision is usually made as an engineering judgement."*

TTI Survey of Winter Weather Flashing Practices

Frozen precipitation and subfreezing temperatures associated with winter weather may impact safety and operations at signalized intersections. Accumulations of frozen precipitation reduce frictional capabilities of roadway pavements. As a result, the driver's ability to safely brake and steer the vehicle is diminished. Sudden acceleration and deceleration may cause complete loss of control. Braking the vehicle to a safe stop while maintaining directional control requires greater time and distance than under normal operating conditions. Likewise, acceleration from a stopped condition must be performed slowly to avoid skidding and sliding. Also, frequent stops during a snowstorm may cause ice to form on intersection approaches. Snow present in the vehicle path is melted by the stopping and starting action of the tires, only to refreeze as a thin sheet of ice when temperatures are at or below freezing. The ability of a driver to control a vehicle is lessened when the icy intersection approach is located on a grade.

Flashing signal operation has been considered as an alternative control strategy when there is ice or snow on the pavement. The advantage of yellow/red flashing operation in winter weather conditions is that major street traffic does not have to stop. Instead, they continue through the intersection, avoiding the stopping and starting difficulties associated with icy pavements. However, there are even fewer guidelines for flashing operation during winter weather than there are for other types of flashing operation. As a result, a second survey was conducted to identify and assess practices related to flashing operation during winter weather periods.

The objective of the survey was to evaluate flashing signal operation as an alternative control strategy during adverse winter weather. Obviously, it is difficult if not impossible to accurately recreate winter driving conditions for the purpose of such an evaluation. Therefore, an attempt was made to identify current practice for improving safety and efficiency when ice or snow is present. A literature review failed to identify any previous studies which addressed the topic of flashing signals during adverse winter weather. Therefore, state and local transportation agencies in several northern states, which experience periods of snow and ice on an annual basis, were contacted to determine how they deal with this issue.

The winter weather survey instrument contained 9 questions. These are shown in Table 3-12. The cover letter and survey instrument are reproduced in Appendix C. The survey was distributed to transportation professionals at 37 state, local, and county agencies. A total of 28 responses (76 percent) were received. The agencies which responded to the winter weather survey are listed in Table 3-13.

Table 3-12. Questions in Winter Weather Survey

Number	Question
1	Does your agency have a policy on traffic signal operations during adverse weather conditions, such as when snow or ice are present on the roadway?
2	If your agency has such a policy, is it a written policy?
3	If your agency does have a written policy, would it be possible for TTI to obtain a copy?
4	What actions, if any, does your agency recommend or mandate for traffic signal operations during snow and/or icy weather?
5	Does your agency ever place traffic signals in flashing mode when snow and/or ice are present on the roadway?
6	If signals are placed in flashing mode when snow and/or ice are present, which of the following apply? Please specify color combination (e.g. - yellow/red or red/red).
7	If signals are placed in flashing mode when snow and/or ice are present, has your agency encountered any problems or difficulties associated with this mode of operation?
8	If signals are not placed in flashing mode when snow and/or ice are present, was this type of operation considered as an option?
9	Please add any comments or suggestions that you may have regarding signal operation during adverse weather conditions, or about flashing signal operation in general.

The responses were analyzed by calculating the percentage selecting each multiple-choice answer. Comments and written responses were summarized for analysis. The response rates for each survey question are summarized in Appendix D.

Table 3-13. Agencies Responding to Winter Weather Survey

State Agencies	County Agencies	City Agencies
Colorado DOT	Arlington County, Virginia	Aurora, Colorado
Delaware DOT	Dakota County, Minnesota	Beloit, Wisconsin
Kentucky Dept. of Highways	Kalamazoo County, Michigan	Boston, Massachusetts
Michigan DOT	Montgomery County, Maryland	Columbus, Ohio
Minnesota DOT - Duluth District	Nassau County, New York	Flint, Michigan
New Hampshire DOT	Waukesha County, Wisconsin	Grand Island, Nebraska
Pennsylvania DOT		Iowa City, Iowa
West Virginia DOT		Lansing, Michigan
Wyoming DOT		Milwaukee, Wisconsin
Virginia DOT		Minneapolis, Minnesota

Winter Weather Flashing Policy (Questions 1-3)

In response to the question "Does your agency have a policy on traffic signal operations during adverse weather conditions, such as when snow or ice are present on the roadway?" only four "Yes" responses (14.3 percent) were received. In each of the four cases, the policy is in the form of verbal instructions issued to signal maintenance personnel, rather than as written instructions or rules for signal operation. Two of the four agencies with policies mentioned the use of flashing operation under certain conditions.

Signal Operation in Snow/Ice Weather Conditions (Questions 4-6)

Responses to the question "What actions, if any, does your agency recommend or mandate for traffic signal operations during snow and/or icy weather?" fell into three general categories: 1) alter signal timings, 2) implement flashing operation, and 3) leave in normal green-yellow-red operating mode. A total of five respondents (17.9 percent) indicated that signal timings are changed to accommodate lower speeds and to reduce the number of required stops. Specific options that were mentioned include changing offsets, extending cycle lengths, and using longer change intervals.

Five agencies (17.9 percent) implement flashing signal operation when snow or ice is present. However, use of flashing signals under such conditions was described as limited. Three of the five agencies implement flashing operation at certain locations where approach grades present difficulties, but again, such applications were described as "occasional" and "isolated." In all three instances, the flashing mode displays a yellow to the major street. One respondent indicated that red/red flash is implemented during maintenance or emergency conditions only. The fifth response was not specific as to the circumstances under which flashing operation is adopted, beyond stating that it is used or has been used when snow or ice is present.

Four responses indicated that normal green-yellow-red signal operation is maintained during adverse weather. It is reasonable to assume that those that do not implement flashing operation or altered timing plans under such conditions allow all signals to operate as usual. Two respondents stated that restoration of the road surface using salt or sand, or removal of accumulated snow and ice by plowing, is an alternative to changes in signal operations.

Difficulties Associated with Winter Weather Flashing Operation (Question 7)

Agencies which utilize flashing signal operation during snow or ice were asked to describe any difficulties associated with this type of operation which they had encountered. None of the five respondents indicated that they had experienced any problems as a direct result of flashing operation. However, one agency mentioned that it had placed several signals in flash during winter months in response to recreational traffic demands, not adverse weather conditions. At one particular location with yellow/red flash, normal operation had to be restored when drifting snow created high snow banks that limited visibility of cross street traffic.

Consideration of Flashing Operation (Question 8)

Those agencies that do not utilize flashing operation were asked if this had ever been considered as an option, and if so, why flashing signal operation had been rejected. Five agencies (17.9 percent) had considered, but rejected, the use of flashing signals during adverse winter weather. Several reasons were cited for these decisions:

- Flashing operation is not easily implemented;
- Consistent application is a potential problem;
- It is difficult to establish criteria for flashing operation;
- Flashing signals during adverse weather do not provide a benefit over normal operation;
- Weather and road conditions generally do not warrant flashing operation;

- Right-of-way control is imperative to avoid bottlenecks given high traffic volumes;
- Vehicle and pedestrian safety; and
- Driver misunderstanding of the meaning of flashing yellow.

Comments on Winter Weather Flashing Operation (Question 9)

The respondents were invited to offer their comments and suggestions regarding flashing signal operations, with respect to both adverse weather operation and normal operations. Many of the surveys were returned with comments, some of which are summarized below:

- Flashing is used for maintenance and emergency conditions only.
- Many locations cannot go into flash operation even during light volumes because of sight distance problems.
- Most of our signals are actuated and if working properly, there is little advantage to placing them in flash mode.
- Flashing would be the wrong approach except on upgrades. Flashing could compound stopping/starting problems.
- The majority of the controllers in (the city) are pretimed solid-state, so each individual controller would have to manually be placed in flash.
- During heavy snowstorms or after repeated storms, large snow banks occur at corners and on median island tips at intersections due to both snow accumulation and snow removal operations. These snow banks may restrict visibility of cross street traffic, and during flashing operation some vehicles may be required to enter the intersection with limited sight distance.
- Accident problems have occurred at flash locations after major snow events and snow removal operations, particularly on median-divided roadways. During snow removal operations, the first priority has been to clear the roadway. As a result, snow is piled on the ends of median islands, and these piles and other snow banks at corners result in the reduced visibility of cross traffic.
- (The city) has an unwritten policy of placing three signal systems on trunk highways within the city into yellow/red flash during snow removal periods. The three intersections are on a hill and maintenance people feel more secure when in flash, warning downhill drivers to prepare to stop for snow removal.

- Most drivers are somewhat accustomed to snowy-icy conditions, and therefore are more likely to slow down and drive according to existing conditions.
- We use red/red flashing operation only during signal maintenance. Flashing signals reduce intersection capacity. We have had some problems with flashing operation for the major approach of an intersection. Some vehicles drive through as if the signal were green.
- The roadway is routinely maintained to reduce the influence of adverse weather. Periods of adverse weather would be difficult to define for most northern jurisdictions with average annual snowfall exceeding single-digit accumulations.
- Recently, we have had several tort liability suits where signals were in planned or emergency flashing operation and there was inadequate sight distance.

Summary of Winter Weather Survey

It is difficult to draw any definitive conclusions based on these findings. However, the results of this limited survey seem to indicate that the use of flashing signals when roadways are icy does not appear to be a common practice. The benefits of this type of operation seem limited to specific intersections where uphill or downhill approach grades have a negative effect upon vehicle braking and steering. The use of flashing operations at other intersections may actually create more problems than it solves, as several of the responses indicate.

Widespread acceptance of this strategy may be impractical for other reasons as well. Determinations of which signals should be placed in flash, when they should be placed in flash, and how long they should remain in flash are difficult decisions requiring much knowledge of highway and traffic conditions. Consistent application of a flashing signal policy for icy roads may not be possible given these limitations.

FHWA Survey of Flashing Practices

As part of an FHWA study of signal operations (6), traffic engineers at state, county, and municipal agencies were surveyed about the use of, and warrants for, flashing signal operation. A total of 232 responses to the questionnaire were received, including 142 from municipal agencies, 49 from counties, and 41 from state departments of transportation. Table 3-14 list the four questions asked about flashing signal operation in this survey and also indicates where the FHWA survey questions correspond to a similar question in the Texas Practices survey.

Table 3-14. FHWA Survey Questions

FHWA Survey Number	Texas Practices Survey Number	Question
1	1, 2	Do you now set certain traffic signals on flashing operation during low volume periods?
2	3	Do you use any warrants for setting signals on flashing operation?
3	---	Which kind of flashing operation do you usually use?
4	7	Have you made any study of the effects of flashing operation on traffic operations or accidents in your jurisdiction?

Use of Low-Volume Flashing Operation (FHWA Question 1)

The first question asked "Do you now set certain traffic signals on flashing operation during low volume periods?" Those that indicated they use flashing were asked to indicate the type of intersections where it was used. Table 3-15 summarizes the results to this question.

This question is similar to Questions 1 and 2 in the TTI Texas practices survey. Approximately two-thirds of the respondents to the FHWA survey indicated that they used low-volume flashing operation. This is about the same response rate indicated in the TTI Texas practices survey. In the second part of this question, agencies were asked to identify the types of intersection and control where flashing operation was implemented. Flashing operation was shown to be used most often at isolated intersections with pretimed signal control, with 80 percent indicating that they used flashing in this situation. This was about twice as common as the use of flashing operation at isolated intersections with actuated control (42.9 percent). Responses to this question indicate that flashing is also used with signal systems, although the survey did not indicate whether the systems were pretimed or actuated.

Warrants for Flashing Operation (FHWA Question 2)

The second question asked "Do you use any warrants for setting signals on flashing operation?" This question is similar to question 3 in the TTI Texas practices survey. Responses to this question are summarized in Table 3-16.

Table 3-15. Responses to FHWA Question 1

Do you now set certain traffic signals on flashing operation during low volume periods?	
Response	**Rate (%)**
Yes	63.4
No	26.6
If Yes, at which type of intersections?	
Type	**Rate (%)**
Isolated, pretimed	80.3
Isolated, semi-actuated	27.2
Isolated, full actuated	15.6
Arterial systems	45.6
Network systems	36.1

Table 3-16. Responses to FHWA Question 2

Do you use any warrants for setting signals on flashing operation?	
Response	**Rate (%)**
Yes	56.9
No	34.1
No Response	9.1

As with the TTI Texas practices survey, about half of the respondents (56.9 percent) stated they did not use warrants for putting signals in flashing operation. Those agencies which indicated that they do have warrants or guidelines most frequently cited hourly volumes less than 50 percent of the MUTCD signal warrants as the basis for flashing operation. The FHWA study theorized that this guideline was the most common because it was in the 1961 MUTCD (18), which was the last edition of the MUTCD to provide a guideline for implementing flashing operation. Other warrants and guidelines that were mentioned included:

- Low-volume periods when intersection spacing does not allow progression.
- On hills during snowstorms to reduce accidents on slippery roadways.
- During low-volume periods in high crime areas.

- When volumes drop to the levels which warrant two-way or four-way stops for at least a six-hour period.
- When volumes are less than 100 vph on the major street and less than 10 vph on the minor street.
- When volumes fall below 325 vph for urban areas or 225 vph for rural areas over a period of four or more hours.
- In high crime areas during low-volume periods in order to minimize the potential for personal assaults against stopped motorists.

Mode of Flashing Operation (FHWA Question 3)

In the third question, the responding agencies were asked "Which kind of flashing operation do you usually use?" The responses to this question are summarized in Table 3-17. The TTI Texas practices survey did not include a question which resembled this FHWA survey question.

Table 3-17. Responses to FHWA Question 3

Which kind of flashing operation you usually use?	
Response	**Rate (%)**
Yellow on the major street, red on minor street	63.4
Red on both streets	8.6
Both	15.9
No response	12.1

Approximately two-thirds of the respondents stated they only use yellow/red flashing operation, with the flashing yellow indication displayed to the major street. Less than 10 percent used only red/red flashing, with most of those being jurisdictions with less than 50 signals. The 18 percent who use both yellow/red and red/red flashing were asked to explain the criteria used to select the flashing mode. Flashing yellow is used on the major street when volumes on the minor street are low. However, for nearly equal major and minor street volumes, flashing red is used on the major street approaches. As a result of accident experience or possible motorist confusion about yellow/red flashing operation, 9 percent of the agencies choose to employ only red/red flashing operation.

Evaluation Flashing Operation (FHWA Question 4)

The final question asked "Have you made any studies of the effects of flashing operation on traffic operations or accidents in your jurisdiction?" This question is the same as question 7 in the TTI Texas practices survey. The responses to this question are summarized in Table 3-18.

Table 3-18. Responses to FHWA Question 4

Have you made any studies of the effects of flashing operation on traffic operations or accidents in your jurisdiction?	
Response	**Rate (%)**
Yes	13.8
No	79.3
No Response	6.9

As with the TTI Texas practices survey, most (79.3 percent) of the respondents had not evaluated flashing operation. Although some agencies stated that they had experienced no problems with flashing operation, most have experienced some type of problems. The FHWA study noted that in cases where an agency had changed low-volume signal operation, in all cases that change had been to eliminate flashing or change to red/red flashing. Most of these changes were in response to accident problems.

Summary of FHWA Survey

Although it is short, the FHWA survey does identify a few key points about flashing operation. It confirms the findings of the TTI Texas practices survey with regards to the use of low-volume flashing signal operation, the existence of guidelines or warrants for implementing flashing operation, and local agency analysis of flashing operation.

The FHWA survey addressed two issues which were not addressed in detail in the TTI Texas practices survey. The survey identified the various types of signal control that flashing operation is used with and the use of the yellow/red and red/red flashing modes. Almost three-fourths of the respondents use either yellow/red or red/red flashing, but not both. The FHWA survey also confirmed the findings of the TTI and Richardson (19) surveys indicating that flashing operation is often used with actuated controllers. Finally, it should be noted that this survey was conducted in the late 1970's, and that signal technology has advanced considerably since that time.

Richardson Survey of Flashing Practices

The City of Richardson, Texas has considered nighttime flashing operation several times during the last ten years. As part of the decision making process, the city conducted a survey of flashing operation in other cities in Texas (19). A total of 11 Texas cities were contacted and asked about their policies for placing signals in nighttime flash. The responses of each city are summarized in the following paragraphs.

Arlington

The City of Arlington implements nighttime flashing operation at intersections with volumes below the signal warrants, unless there are sight distance restrictions or a previous accident history at an intersection. All of the intersections in the city use actuated control. Arlington has not experienced a significant change in accidents at these locations, nor have they experienced complaints from the public or police.

Corpus Christi

The City of Corpus Christi uses nighttime flashing operation at certain intersections with pretimed control. They do not use nighttime flashing operation at actuated intersections unless the intersection is on an arterial with a speed limit of 45 mph (70 km/h) or higher. The guideline used by Corpus Christi for implementing flashing operation is a volume less than 70 percent of the signal warrant volume for eight or more consecutive hours. Corpus Christi has not experienced a notable increase in nighttime flashing accidents.

Dallas

The survey indicated that the City of Dallas does not have any standard guidelines for flashing, except that intersections considered for nighttime flashing operation cannot have a sight distance restriction or history of accidents. Dallas is unique in that there are both dry and wet areas in the city. Intersections in the dry areas begin flashing at 10:30 pm and intersections in the wet areas begin flashing at 2:30 am. All intersections are returned to normal operation at 6:00 am. Flashing is used with both pretimed and actuated controllers. The city has received some citizen complaints that there are too many signals on flash. The city has not performed an analysis of flashing accidents, but if there appears to be a significant increase in accidents at a flashing intersection, then the signal is returned to normal operation.

Farmers Branch

The City of Farmers Branch has only one intersection which uses flashing operation. It is located near a school and only operates before and after school. There are 48 signals in the city, all of which are actuated, and they are placed in free operation after 8:00 pm. The survey indicated that Farmers Branch was about to begin a program of dimming yellow and green indications between 10:00 pm and 6:00 am. The city estimated that doing so would reduce electrical consumption by 40 percent during this period and reduce the city's total electric bill for signals and street lights by 5 percent.

Garland

The City of Garland was in the process of removing nighttime flashing operation at the time of the survey (Fall 1991), as they were replacing their pretimed controllers with actuated controllers which were to use 24-hour normal operation. Garland has not analyzed accidents at nighttime flashing intersections, but they were unaware of any substantial increase in the number of accidents.

Grand Prairie

The City of Grand Prairie has no guidelines for nighttime flashing operations, although they have a small number of intersections that use nighttime flashing operation. All of these intersections have actuated control. The city stated that accidents at these intersections have decreased since nighttime flashing operation was initiated.

Irving

The City of Irving uses flashing operation at ten signalized intersections in the city, eight of which are in the downtown area and use pretimed control. These intersections flash from 10:00 pm to 5:00 am, and the city has not noticed any change in the accident rate at these intersections.

Lubbock

The City of Lubbock places its traffic signals in nighttime flash when volumes are less than 80 percent of the warrants used to install the signal. Most of the signals in the city are actuated and begin flashing at 10:00 pm or midnight. The downtown area has pretimed controllers and begins flashing at 6:30 pm. They do not use nighttime flashing operation at arterial-arterial intersections. The city has not analyzed accidents related to nighttime flash, but they have not noticed any difference in accidents between flashing and normal operation intersections.

Mesquite

The City of Mesquite was considering nighttime flashing operation on a city-wide basis at the time of the survey, but had yet to make a decision. They do have one signal near a school which flashes at all times except before-and-after school.

Richardson

The City of Richardson considered a blanket policy for night flash in 1990, but did not place the signals in flash as the staff found that delay savings were minimal during late-night early-morning hours compared with traffic actuated operation. Richardson's controllers have the capability of omitting protected phases by time-of-day. This feature combined with protected/permitted left-turns could be used to revert the intersections from 4-6 phase to 2-phase operation during off-peak conditions. Richardson plans to study this early next year after completing a traffic count system that will provide the data for such an analysis.

San Antonio

The City of San Antonio has no established policy for nighttime flashing operation. It currently uses flashing operation with both pretimed and actuated controllers. San Antonio is the only city surveyed in which a citizen request is necessary for an intersection to be considered for nighttime flash. If a request is made and all of the factors listed below are met, the signal is placed in nighttime flash. San Antonio has not performed any analysis of accidents associated with nighttime flash.

- No sight distance or visibility restrictions.
- Speed limit less than 45 mph (70 km/h).
- Not an accident-prone intersection.
- High "A" nighttime level-of-service.

Summary of Richardson Survey

The findings of the Richardson survey appear to contradict some of the findings of the FHWA survey and some of the findings of previous research studies described in Chapter 2. The Richardson survey indicated that many municipalities use flashing operation with actuated controllers and that most of the agencies with flashing operation have not experienced an increase in accidents, and one city even found a decrease in accidents with flashing operation.

As with the other surveys, the Richardson survey indicated that there are no guidelines for flashing operation which are used on a consistent basis, and in fact, several cities make decisions on flashing operation purely on the basis of engineering judgement without the assistance of guidelines. However, in making a decision, most cities do consider sight distance and accident history.

One of the traffic engineers responding to the Richardson survey commented that nighttime flashing operation reduces the potential for liability as a result of an accident. He stated that there can be no debate about which driver failed to yield the right-of-way, nor can there be a claim of conflicting green indications or inadequate clearance time.

MUTCD Guidelines for Flashing Signal Operation

The national *Manual on Uniform Traffic Control Devices* (MUTCD) (20) provides standards for the design and use of traffic control devices on streets and highways. The MUTCD and its related documents are the primary source of information on the use of traffic control devices, including traffic signals, and it is usually the first document that most traffic engineers refer to when evaluating the need to implement flashing operation. The national MUTCD is published by the Federal Highway Administration. The Texas version of the MUTCD (1) (TMUTCD) is based on the national Manual, but includes additional material to account for Texas conditions and practices. The TMUTCD is issued under the legal authority of Texas state law, and all traffic control devices in the state are required by law to conform to the standards in the TMUTCD. There have been several editions of the Texas and national MUTCDs. The manner in which the various editions address flashing operation has changed several times over the years. A review of the standards in each edition gives some insight into how flashing signal operation has been implemented in the past.

Texas MUTCD

The current edition of the Texas MUTCD contains several guidelines related to the use of flashing operation. These guidelines are located in several different sections in Part IV (Signals) of the Manual. These guidelines are consolidated in Appendix E for convenience and are discussed on the following pages. Early editions of the Texas MUTCD were also reviewed in an attempt to determine the origin of the current guidelines for flashing operation.

Guidelines on When to Implement Flashing Operation

Section 4B-18 of the 1980 Texas MUTCD (1) describes how the switch should be made from normal (or stop-and-go) to flashing operation and vice versa. This section also describes when it is appropriate to implement flashing operation. A portion of this section states:

> *When for a period of four or more consecutive hours of the late evening and/or early morning periods, any traffic volume drops to 50 percent or less of the stated volume warrants, pretimed traffic control signals should be placed on flashing operation rather than continue normal operation.*

Although this guideline appears in the Texas version of the MUTCD, it is not contained in the national MUTCD. Although it is not specifically stated in the TMUTCD, it seems appropriate that the volume warrants to which this statement refers are Warrant 1 - Minimum Vehicular Traffic (Section 4C-3) and Warrant 2 - Interruption of Continuous Traffic (4C-4). Table 3-19 summarizes the minimum volumes for these warrants. However, these volumes may be reduced by 30 percent when the 85th percentile speed on the major street exceeds 40 mph (65 km/h) or when the intersection lies within the built-up area of an isolated community having a population of less than 10,000. Therefore, flashing operation should be implemented when volumes are 50 percent of the volumes in Table 3-19 and the signal has a pretimed controller.

Table 3-19. Traffic Signal Warrant Volumes

Roadway	Number of Approach Lanes	Minimum Volume (vph)		Reduced Volume (vph)[5]	
		Warrant 1[3]	Warrant 2[4]	Warrant 1[3]	Warrant 2[4]
Major[1]	1	500	750	350	525
	2 or more	600	900	420	630
Minor[2]	1	150	75	105	53
	2 or more	200	100	140	70

Notes: [1] Total of both approaches
[2] Higher volume approach (one direction only)
[3] Minimum Vehicular Volume warrant
[4] Interruption of Continuous Traffic warrant
[5] Speed > 40 mph (65 km/h) or population < 10,000
Source: Reference (1)

The 50 percent of warrant guideline described above has been included in every edition of the Texas MUTCD. Each of the previous editions of the TMUTCD addressed flashing operation of pretimed and actuated signals separately from one another. However, the justification for using 50 percent of the signal warrants as the threshold value for implementing flashing operation could not be identified, although its first use in the MUTCD can be traced to the 1948 edition of the national MUTCD (21). It was most likely an arbitrary selection based on engineering judgement, as has been suggested in a study of flashing signal operation (22).

Flashing of Pretimed Traffic Signals - The 1954 Texas MUTCD (23) states that if volumes fall below 50 percent of the minimum warranting volumes for a period of **two** or more consecutive hours, then flashing operation should be substituted for normal signal operation. It recommends that flashing operation be limited to no more than three periods in 24 hours. The 1967 Texas MUTCD (24) increased the number of hours of a reduced volume level (50 percent of warrant volumes) to four hours for flashing operation to be implemented. This guideline has remained in the Texas MUTCD in both the 1973 (25) and 1980 (1) editions. It is worth noting that the language used with this guideline has changed over the years. Table 3-20 summarizes the TMUTCD guidelines for flashing operation of pretimed signals, and it also includes the language used with these guidelines.

Table 3-20. TMUTCD Guidelines for Flashing Operation of Pretimed Traffic Signals

TMUTCD Edition	Flashing Recommendation	Volume Requirement	Time Requirement	Other Requirements
1954	Flashing shall be substituted for normal	Below 50% of warrant	2 or more consecutive hours	Not more than 3 periods/24 hours
1967	Desirable to substitute flashing for normal	50% or less of warrant	4 or more consecutive hours	Not more than 3 periods/day
1973	Should be placed in flashing rather than continue normal	50% or less of warrant	4 or more consecutive hours	Late evening/ early morning
1980	Should be placed in flashing rather than continue normal	50% or less of warrant	4 or more consecutive hours	Late evening/ early morning

Flashing Operation of Actuated Traffic Signals - The 1980 TMUTCD does not contain a guideline related to flashing operation of actuated traffic signals. However, all three previous editions address this situation. The 1954 TMUTCD (23) states that actuated signals should be operated at all times as stop-and-go devices except when controlled by emergency vehicles or when failure prevents normal operation. The 1954 edition contains the statement *"Since traffic-actuated signals, properly timed, cause a minimum of unnecessary delays, there is no justification for changing them to flashing operation during light traffic periods."*

The 1967 Texas MUTCD (24) increased the flexibility to implement flashing operation of actuated signals. It states that actuated signals should normally be operated at all times as stop-and-go signals, but may be placed on flashing operation for special circumstances such as: during breakdowns, repairs, and maintenance; in conjunction with nearby pretimed signals on flashing operation; and upon preemption by a railroad signal. The 1973 TMUTCD (25) contained the same guideline as the 1967 edition with regards to flashing operation of actuated signals. Table 3-21 summarizes the development of guidelines for flashing actuated signals.

Table 3-21. TMUTCD Guidelines for Flashing Operation of Actuated Traffic Signals

TMUTCD Edition	Flashing Recommendations	Exceptions	Comments
1954	Normal operation should be used at all times	Emergency vehicle signal When failure prevents normal operation	No justification for changing to flashing during light volumes
1967	Normal operation should be used at all times	Breakdowns, maintenance With flashing pretimed signals Railroad preemption	None
1973	Normal operation should be used at all times	Breakdowns, maintenance With flashing pretimed signals Railroad preemption	None
1980	Not specifically addressed		

Guidelines for Color Indications of Flashing Operation

Section 4B-6(7) of the 1980 Texas MUTCD (1) describes the color indications that should be used in flashing operation. Portions of this section state:

> *When a traffic control signal is put on flashing operation, normally a yellow indication should be used for the major street and a red indication for the other approaches. Yellow indications shall not be used for all approaches. ... A CIRCULAR YELLOW indication shall be flashed instead of any YELLOW ARROW indication which may be included in that signal face. ... All signal faces on an approach shall flash the same color of circular indication, except that left turn signal indications may be flashed CIRCULAR RED when adequately shielded or positioned so that through traffic on the approach will not be exposed to substantial visual conflict from the left turn signal indications. The flashing yellow signal indication for through traffic does not have to be shielded or positioned to prevent visual conflict for drivers in the turn lane.*

Earlier editions of the Texas MUTCD use the same basic philosophy as the current edition, although the 1967 TMUTCD (24) also contains the following consideration:

> *"If the safe approach speed on one street differs from the safe approach speed on the other street or streets, the street having the higher safe approach speed should be given the*

flashing yellow indication and the other approaches should be given a flashing red indication."

It is worth noting that the MUTCD only describes the use of the yellow/red flashing operation and that the red/red flashing operation is not specifically mentioned.

National MUTCD

The national MUTCD establishes standards for the design and use of traffic control devices used throughout the United States. All states are required to adopt the national MUTCD or develop a state manual in substantial conformance with the national MUTCD, as Texas has done. The 1954, 1967, 1973, and 1980 Texas MUTCDs are based on the 1948 (21), 1961 (18), 1971 (26), and 1978 (27) national MUTCDs, respectively. Therefore, the previous discussion about flashing operation in the Texas MUTCDs also applies to the respective national MUTCDs, with one exception. The 1971 and 1978 national MUTCDs (26, 27) do not contain the statement that pretimed signals should be placed in flashing operation when volumes are 50 percent or less of the warrant volumes for four or more hours. Therefore, the 1961 MUTCD (18) was the last edition of the national Manual to include a guideline indicating when flashing operation should be used.

Traffic Control Devices Handbook

The *Traffic Control Devices Handbook* (28) (TCDH) is a companion document to the 1978 national MUTCD (27). It provides background information to assist the traffic engineer in satisfying the standards contained in the 1978 MUTCD. The TCDH contains some information about flashing operation of traffic signals. It states that some of the benefits of flashing operation are:

- Reduces stops and needless delay to major street traffic.
- Reduces delay to side street.
- Less stops and delays will result in a reduction in fuel consumption.
- Electrical consumption by the traffic control signal can be reduced by 50 to 65 percent.

The TCDH describes a number of conditions which must be taken into account in making a decision about flashing operation of traffic signals. These conditions include:

1. Flashing yellow/red operation may be appropriate at simple, four-legged or three-legged, intersections where the minor street drivers have an unrestricted view of approaching major street traffic, and the traffic volumes are low.
2. At locations that flash yellow/red, the accident patterns should be monitored. Signal operation should be changed to normal operation if the accident pattern and/or severity increases or if an increase in conflicts is perceived. Indications that a potential problem exists may include:
   a) A short-term rate of 3.0 right-angle accidents in one year.
   b) A long-term rate of 2.0 right-angle accidents per million vehicles entering during the flashing operation if the rate is based on three to five observed right-angle accidents.
   c) A long-term rate of 1.6 right-angle accidents per million vehicles entering during flashing operation if the rate is based on six or more observed right-angle accidents.
3. A speedway effect can be avoided and uniform speeds can be achieved by maintaining enough operating signals at an appropriate spacing to provide signal progression at the desired speed.

The second guideline in the TCDH was taken from a Federal Highway Administration (FHWA) research report (6), which is described in detail in Chapter 2. The first and third guidelines appear to be based on conventional traffic engineering wisdom.

Agency Guidelines For Flashing Signal Operation

The review of current practice identified several agencies which have developed written guidelines for implementing flashing operation of traffic signals. These guidelines are based on a variety of different factors, but most are related to the use of flashing operation during low-volume periods. Guidelines were identified for two states (Pennsylvania and Texas) and two local agencies (Arlington and Richardson). The are described in the following paragraphs.

Arlington Flashing Signal Guidelines

The *Traffic Signal Applications Manual* (29) for the City of Arlington, Texas contains a form which is used to determine whether flashing operation is appropriate at a given intersection. The procedure consist of three parts which address volume criteria, intersection characteristics criteria, and accident history. The volume criteria has two options: 1) major street bi-directional volume less than 200 vph for at least three hours between 10:00 pm and 8:00 am, or 2) less than 50 percent of Warrant 1 volumes for at least three hours between 10:00 pm and 8:00 am and a major to minor street ratio of three or more. If the intersection meets one of these criteria, then the analysis procedure continues to the intersection characteristics criteria. There are two parts in this criteria and **both** must be satisfied. The first part requires the intersection to be within 1000 feet (300 meters) of a regular signalized intersection not installed under the accident warrant, or that the signal in question was not installed under the progressive or accident warrants. The second part of the criteria requires the minor street to have sight distances adequate for 10 mph (15 km/h) in excess of the major street posted speed limit. If both parts are satisfied, the analysis continues to the accident history. This criteria considers the 24-month accident history for nighttime right-angle and driving-while-intoxicated (DWI) accidents during the period of concern to the same types of accidents over a 24-hour period. The analysis procedure does not establish definitive rates above which flashing operation is not recommended. Instead, the decision is a subjective one made by the engineer.

If the criteria in all three parts are satisfied, the engineer may consider flashing operation at the intersection in question. If any of the three criteria are not met, flashing operation is not recommended. The evaluation form used by the City of Arlington is contained in Appendix F.

Pennsylvania Flashing Signal Guidelines

The Pennsylvania *Traffic Engineering and Operations Manual* (30) contains a brief description of the procedure to be followed in evaluating the need for flashing operation at a signalized intersection. This description indicates that flashing operation should be used when the total volume drops below 325 (urban) or 225 (rural) vph for a period of four or more hours. Exceptions to this policy will be considered at those locations where a sight distance problem exists, the accident pattern or severity increases after flashing is initiated, or an increase in unsafe conflicts is observed.

Richardson Flashing Signal Guidelines

The City of Richardson, Texas has been evaluating the use of late-night flash over the last two years. These evaluations were spurred by citizen complaints of excessive minor street delay during late-night periods and city council request to evaluate the effectiveness of flashing operation. In response to the complaints/request, the city staff developed guidelines for implementing flashing operation during nighttime periods at selected intersections. The following conditions must be present for flashing operation to be implemented:

- Traffic volumes less than 50 percent of volumes for signal Warrant One (less than 300 vph for both directions of the major street and less than 75 vph on one approach of the minor street).
- Not a hub intersection.
- Accident experience less than three accidents per year between 7:00 pm and 7:00 am.
- Adequate sight distance.
- No adjacent railroad crossing or fire station.
- Normal operation negatively impacts signal coordination.
- Time of flashing operation:
  - 11:00 pm to 6:00 am, Sunday night through Wednesday night.
  - 2:45 am to 6:00 am, Thursday night through Saturday night.

Flashing operation was implemented at 43 of the city's 81 signalized intersections. The perceived benefits of the flashing program include reduced driver delay, reduced driver frustration, and reduced electrical consumption. A flowchart indicating the city's flashing signal policy is contained in Appendix F.

Texas Flashing Signal Guidelines

As previously described, Section 4B-18 of the Texas MUTCD (1) states that flashing operation should be used with pretimed signals when traffic volumes drop to 50 percent or less of the warrant volumes.

Conclusions from Review of Current Practice

Several surveys addressing the use of flashing signal operation were conducted or identified. The most extensive is the TTI Texas current practices survey, which was conducted as part of this research study to identify how flashing operation is utilized in Texas. An adverse weather survey was also conducted to identify how agencies in northern climates use flashing operation during periods of snow or ice. The FHWA survey was conducted about 15 years ago and is the most limited of the surveys. Another survey was conducted by the City of Richardson and identifies the various flashing signal operations in Texas. The responses to the questions in these surveys identifies some of the flashing signal practices in Texas and the United States and also provides some insight into the decision-making process related to implementing flashing operation. The following conclusions can be drawn from the results of the various flashing signal surveys:

- Flashing operation of traffic signals is a widely used practice.
- Some types of flashing operation are more common than others. Among the most common forms of flashing operation are:
    - Emergency or conflict flash.
    - Signal installation and/or removal.
    - Low-volume periods, typically late-evening/early-morning hours.
    - Railroad preemption.
- There is a lack of adequate guidelines for implementing flashing operation; therefore, the decision to implement flashing operation varies widely from one locale to another.
- There is a significant interest in the development of guidelines for flashing traffic signal operation.
- Several different factors are typically considered when evaluating whether to implement flashing operation. The most commonly considered factors are:
    - Traffic volume.
    - Traffic volume as a percentage of signal warrant.
    - Time of day.
    - Accidents.
    - Day of the week.

- The use of flashing operation within the same geographic area may vary between neighboring agencies.
- Although flashing operation appears to be more common with pretimed controllers, it is also often used with actuated controllers.
- Although flashing operation is widely used, few agencies have evaluated the effectiveness of flashing operation.
- Selecting the mode of flashing operation (yellow/red or red/red) varies between agencies. The following factors are considered by some agencies in deciding the mode of flashing:
    - ▸ Volumes.
    - ▸ Accident history.
    - ▸ Consistency with other flashing signals.
    - ▸ Geometrics and sight distance.
    - ▸ Speeds.
- It is not unusual to use both modes of flashing operation at the same intersection. Yellow/red flash is used for low-volume or other normal flashing operation and red/red flash is used for emergency flashing operation.
- Traffic engineers are concerned with driver understanding of flashing operation, particularly with respect to whether drivers recognize that major street traffic may be facing a flashing yellow indication.
- The use of flashing operation of traffic signals as a response to snowy or icy weather does not appear to be a common occurrence.
- Many of the agencies which have implemented flashing operation have not experienced an increase in accidents at those intersections with flashing operation.
- Dimming the signal indications at night may reduce electrical power consumption.
- Some agencies start flashing operation for all signals at one time instead of varying the start of flashing operation according to the volume levels at a specific intersection.
- Some agencies delay the start of flashing operation on Thursday through Saturday nights until after the nightclubs have closed.
- Traffic engineers are concerned about driver behavior at intersections which may use yellow/red during low-volume flashing and red/red for emergency flash.
- The guidelines found in the MUTCD for flashing signal operation are limited.
- The Texas MUTCD states that flashing operation can be implemented at intersections with pretimed control when volumes are 50 percent of the signal warrant volumes for 4 or more

hours. However, it makes no mention of the use of flashing operation with actuated controllers. The national MUTCD does not contain any mention of when it is appropriate to use flashing operation.

- Previous editions of both the national and Texas MUTCDs contained more detailed guidelines about when flashing operation could be used.
- The origin of the 50 percent of warrant volumes for implementing flashing operation could not be identified. The decision to use 50 percent was most likely based on engineering judgement.
- The MUTCD (both Texas and national) do not mention the use of the red/red flashing mode.
- The MUTCD states that a flashing yellow indication should normally be displayed to traffic on the major street.
- The MUTCD states that if a flashing red indication is used for the left-turn movement and a flashing yellow is used for the through movement, the flashing red indication should be shielded or positioned to that through traffic will not be exposed to visual conflict from the left-turn indication.

CHAPTER 4
OPERATIONAL ANALYSIS

The operation of traffic signals is one of the primary factors to be considered in a decision to implement flashing operation. The operational concerns are primarily centered on the impact of flashing operation on vehicular delay. This chapter describes an evaluation of the operational impacts of flashing operation during low-volume conditions. The findings of previous research on the subject are described first, followed by the findings of the operational analysis of low-volume signal operation. The analysis calculated vehicular delay for various intersection scenarios. The scenarios were created by combining various options for the five intersection characteristics shown in Table 4-1.

Table 4-1. Intersection Characteristics for Analysis Scenarios

Type of Signal Control	Geometrics (Major St. × Minor St.)	Type of Intersection Control	Volume Categories(vph)	
			Major St.	Minor St.
Red/red flashing Yellow/red flashing Pretimed Actuated	5 lanes × 4 lanes 5 lanes × 2 lanes 4 lanes × 2 lanes 2 lanes × 2 lanes	Isolated System Diamond	0-125 126-250 251-500	0-125 126-250 251-500

Previous Research on Operational Aspects of Flashing Signals

Vehicle delay expressed in one form or another is one of the most widely used measures-of-effectiveness in traffic operations analysis. Many documents, such as the *1985 Highway Capacity Manual* (HCM) (31) and the *Traffic Control Systems Handbook* (32), offer mathematical equations for the computation of stopped delay, random arrival delay, and others. Because a yellow/red or red/red flashing signal operates in the same manner as a two-way or four-way stop controlled intersection, the procedures used to analyze stop controlled intersections are typically also used for flashing signal operation. The 1985 HCM is the most well known document containing procedures for estimating the capacity of stop-controlled intersections. Recently, the Transportation Research Board (TRB) published revised procedures for the evaluation of capacity and level of service (LOS) at unsignalized intersections (33).

Various studies have compared the differences in delay between flashing signal (or stop controlled) and normal signal operation. A study of eight intersections with two-way and four-way stop control, pretimed, or actuated signal operation (34) developed stopped time delay estimates for an average hour, as shown in Table 4-2.

Table 4-2. Hourly Delay Values

Type of Control	Stopped Time Delay During an Average Hour
Two-way Stop	0.96 hours
Four-way Stop	1.61 hours
Pretimed Signal	1.67 hours
Actuated Signal	1.09 hours

Source: Reference (34)

Probably the first simulation comparing flashing signal operation to normal operation was conducted in the early 1960's (22). This study found that when traffic volumes on all approaches to an intersection were low, regular signal operation, as opposed to flashing operation, does not benefit traffic on any approach from the standpoint of delay, convenience, and accident potential. The conclusion of the study was that a signal should be placed in flashing operation when the actual traffic volumes fall below the signal warrant volumes. At the time of the study, the 1961 MUTCD (18) recommended placing signals in flashing operation when the volumes were 50 percent of the warrant volumes for four or more consecutive hours. Therefore, the study further concluded that the MUTCD flashing signal guideline was too low.

A study of traffic signal warrants for pronounced peak periods (35) identified the minor street hourly volume at which stop sign control (or yellow/red flashing) and normal signal operation produce equal total minor street delay. This relationship is shown in Table 4-3. These minor street volumes represent the volume below which normal signal operation was not recommended by the study researchers as it would increase rather than decrease minor street delay. The study recommended that flashing signal operation be used when the minor street volume fell below these values.

Table 4-3. Equal Signal and Stop Control Delay

Type of Intersection	Number of Minor Street Approach Lanes	Minor Street Volume Where Stop and Signal Delay are Equal
3-Way	1	100
4-Way	1	150
3-Way	2	300
4-Way	2	400

Source: Reference (35)

The FHWA study (6) described in Chapter 2 includes a detailed comparison of flashing signal operation to several alternative types of normal signal operation. The FHWA study derived mathematical equations based upon traffic flow theory for predicting stopped-time delay for red/red flashing, yellow/red flashing, pretimed, semi-actuated, and fully actuated signal operation. Stopped delay data was collected in the field to validate the models. The predicted stopped time delay was found to be close to the delay measured in the field. The field data (stopped time delay) was also used to develop simple relationships for a wide range of signal control strategies. Table 2-12 (see page 2-16) indicates the expected stopped delay found in the FHWA study for the different signal control strategies. The FHWA study used the stopped delay values in Table 2-12 for the major and minor street and weighted the delay by approach and intersection traffic volume to yield Figure 4-1.

From Figure 4-1, the following general conclusions were reached about how flashing operation affects stopped time delay relative to other forms of signal operation:

- Yellow/red flashing operation produces less stopped delay than any form of regular operation under all combinations of major and minor street volumes.
- Red/red flashing operation produces less stopped delay than pretimed operation under all traffic volume combinations, even where signals are coordinated on an arterial or in a network.
- Red/red flashing operation produces more stopped delay than fully actuated and semi-actuated, isolated operation at all volume ratios.
- Except at volume ratios above nine, red/red flashing operation produces less stopped delay than semi-actuated signals with a background cycle.

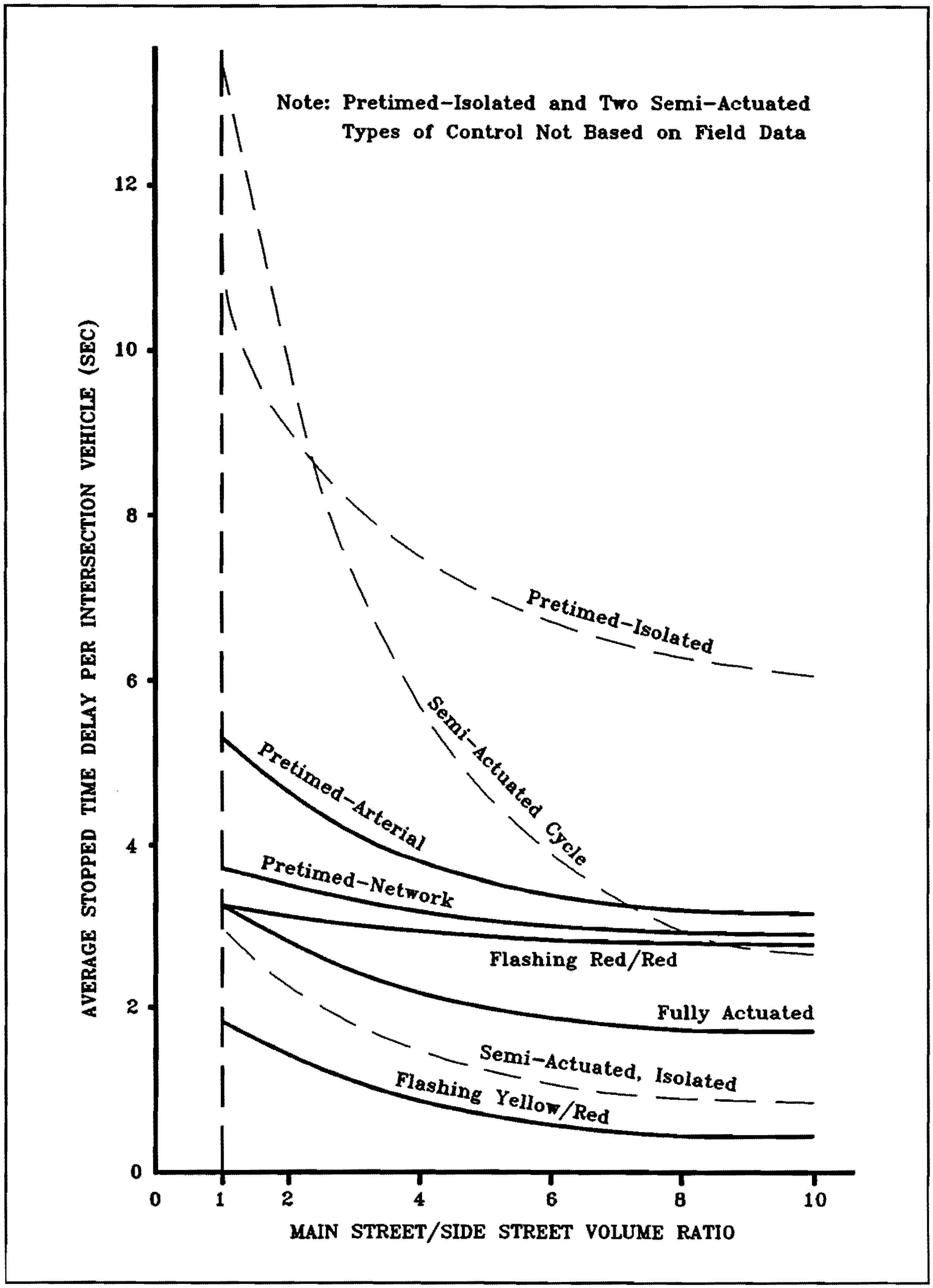


Figure 4-1. Average Stopped Delay Per Intersection Vehicle
Source: Reference (6)

Because limited research has been conducted in the area of flashing signal operation, this study initiated a separate operational analysis of signal operation, as will be discussed in this chapter. It is the intent of this study not to repeat research efforts conducted by others, but to explore alternative measures-of-effectiveness in order to help identify contrasts between flashing and normal signal operation.

Traffic Signal Simulation

The study of flashing signal operation is best performed when there is a complete signal system to be changed from normal to flashing operation, or vice versa. The signal system can be an arterial or a particular area, such as a Central Business District. Pertinent data would be collected before and after the change, and any differences in measures-of-effectiveness (MOEs) would be evaluated. Unfortunately, such a change-over was not available at the time of this study.

An alternative approach involves the use of traffic signal simulation software. Because actual traffic data was not readily available, a hypothetical intersection with simple and fundamental operational parameters was used. A hypothetical intersection was a practical way to demonstrate the project's objectives: comparing the flashing operation to the normal operation. The hypothetical intersections, as described below, depict intersections of a typical environment. This approach produces practical and usable data for traffic engineers in the field. Because each site condition might possess unique characteristics not common to other locations, the typical hypothetical approach gives the traffic engineer a "ground-zero" starting place. If the traffic engineer has a location that possesses circumstances that affect traffic delay, then the traffic engineer can adjust the results to suit the conditions. A more detailed explanation of how site conditions may/may not affect traffic delay as it relates to signal operation is discussed later in this chapter.

Traffic simulation models were used to compare flashing operation to several alternative forms of signal operation. The comparison of signal operation utilized delay as the MOE. Total delay per vehicle, calculated using the difference between desired and actual travel time through the intersections, was used exclusively as the measure-of-effectiveness. Subsequent references to delay imply the total intersection delay and delay per vehicle.

The simulation analysis explored the relationship of varying traffic volume to delay for four different geometric configurations. The four geometric configurations analyzed were: 5 (lanes) × 4 (lanes), 5×2, 4×2, and 2×2. Each geometric configuration was a four-legged intersection (90 degree angle relationship). Analyses were performed for an isolated intersection, a three intersection signal system, and a diamond interchange. Because the diamond interchange is geometrically (intersection spacing, etc.) and operationally different (provision for overlap, etc.) as compared to the four-legged intersection, it is discussed separately later in this chapter.

For the four-legged intersections, the traffic volume on the major and minor streets was varied through a range between 10 and 500 vehicles per hour (vph) per approach. The highest traffic volume simulated was determined by using approximately one-half of the highest volume found in the MUTCD traffic signal Warrants 1 and 2. Flashing yellow/red, flashing red/red, pretimed, and actuated signal operation were each modelled using identical traffic volume scenarios. Signal timings for the normal operation were developed for optimal operation based on proportion of traffic volume. Signals in a system were optimized for platoon progression.

Simulation Models

Two different computer simulation models were used in the analysis: the TEXAS model and the TRAF-NETSIM model. Both of the models were used in the analysis of an isolated intersection. However, because the TEXAS model can only model a single intersection, the NETSIM model was used for the signal system. Both models are microscopic and stochastic (i.e., random). However, there are some significant differences between the two models. As mentioned, the TEXAS model could not be used for the signal system analysis. However, the TEXAS model is the only one of the two that could model red/red flashing operation. Therefore, the analysis of the signal system which was conducted with the NETSIM model did not include analysis of red/red flashing operation. Table 4-4 compares the capabilities of the two models.

The TEXAS Model was developed by the University of Texas at Austin for the TxDOT Through the years, the model has been calibrated to model existing conditions as closely as possible. Research indicates that the TEXAS Model adequately simulates most existing conditions (36). Version 3.11 of the TEXAS Model was used in the simulation as its coding has been improved to more accurately represent delay at four-way stop controlled intersections (37). Earlier versions overestimated delay at four-way stop controlled intersections (38).

Table 4-4. Comparison of Analysis Models

Capabilities	NETSIM Model	TEXAS Model
Stochastic	✓	✓
Yellow/Red Flashing	✓	✓
Red/Red Flashing		✓
Pretimed	✓	✓
Fully Actuated	✓	
Semi-Actuated	✓	✓
Isolated Intersection	✓	✓
Signal System	✓	

Version 3.11 of the TEXAS Model cannot model a fully-actuated controller with the Memory-Off feature. This is to say that once a vehicle has been detected, then the appropriate phase will be called, even if the vehicle leaves the detector before the phase is serviced. Current actuated controller operation commonly uses the Memory-Off (also referred to as non-locking) function with a presence detector. The Memory-Off places a call until the vehicle leaves the loop; then the call is dropped. Because the version of the TEXAS Model used in this analysis did not have the Memory-Off function, the delay results are slightly higher than they would be if this feature could be accurately modeled. Because of the low volumes present in the simulations, it is doubtful that there would be a significant difference between the calculated delay and actual delay. It should be noted that a more recent version of the Texas Model now has that capability.

Version 3.0 of the NETSIM model can accurately model both an isolated intersection and a signal system. However, the NETSIM model does not have the capability to simulate a four-way stop controlled intersection, meaning that it could not model red/red flashing operation. The NETSIM model was used solely to simulate the signal system. The NETSIM model has been proven to simulate traffic conditions fairly well.

Because both models are stochastic (i.e., involving a random variable, chance, or probability), a minimum of five replicate runs were made for each traffic volume scenario used in the analysis. The average total delay and average traffic volume were computed based on individual results from each run made.

Simulation Assumptions

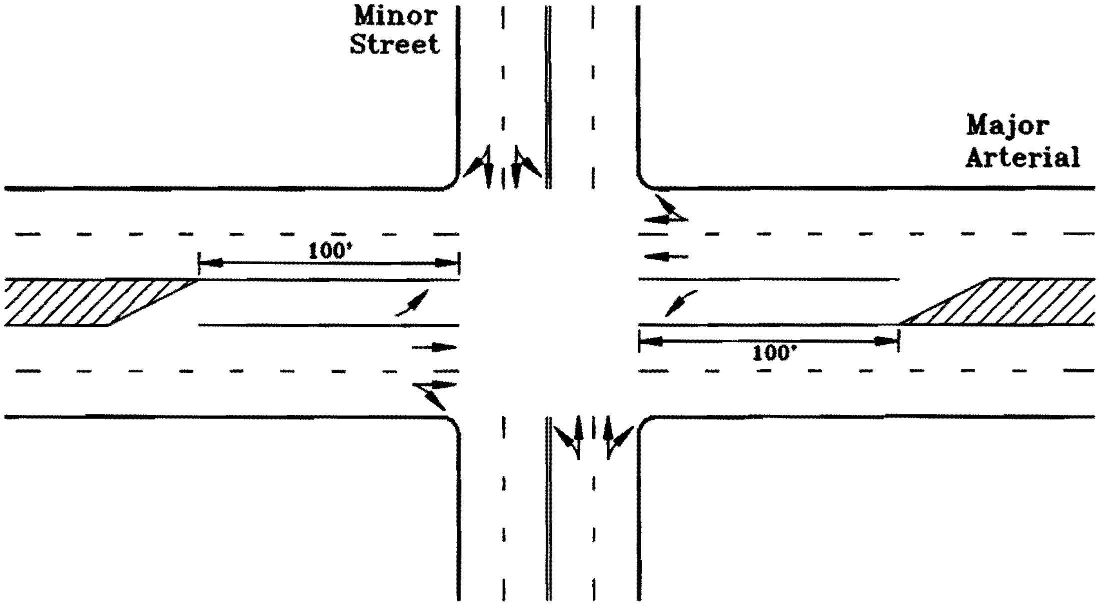
Because this study of signal operation was not based on existing or "real world" intersections, many assumptions regarding geometric and operations had to be made. However, in most cases, the model's encoded default parameters were used. Both the TEXAS and NETSIM models have been verified to yield credible results to actual conditions. As a rule, operational parameters that affect the many algorithms, such as the "car following" or start-up lost time were not changed. Only basic changes in geometric and signal operation were made.

Geometric Properties for Isolated and Signal System

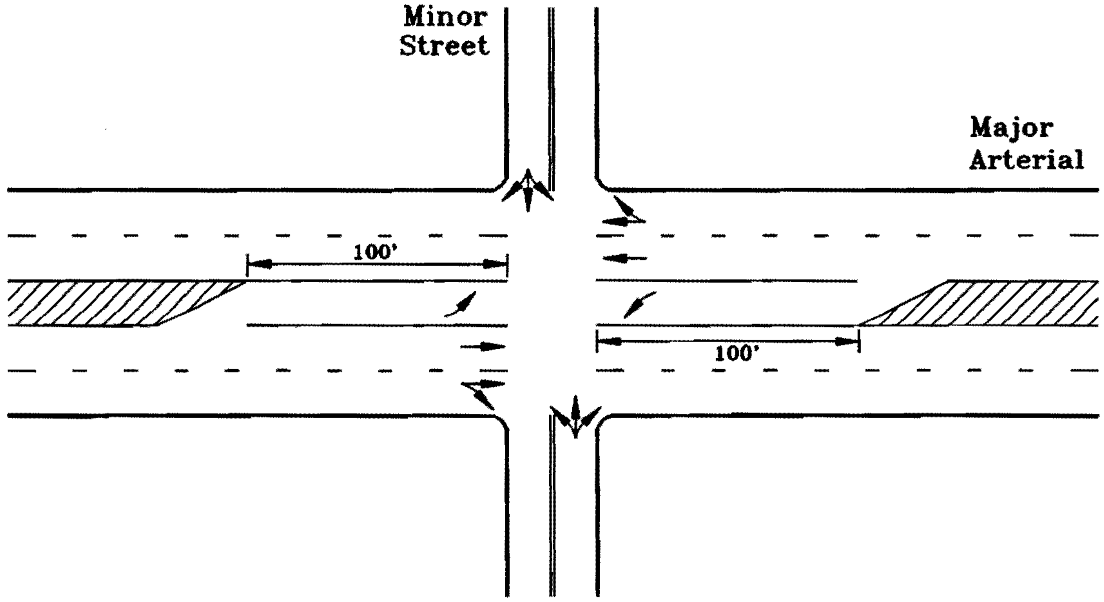
Four intersection types were modelled: 5 (lanes) × 4 (lanes), 5×2, 4×2, and 2×2. These configurations are illustrated in Figures 4-2 and 4-3. The geometric designation represents the total number of lanes across the major street and the minor street. The total number of lanes includes both directions of traffic. For example, the 5×4 geometric configuration has 5 lanes on the major street and 4 lanes on the minor street. Lanes are 12 feet (2.7 meters) wide for all geometric configurations. For the intersections that include an exclusive left-turn lane, the storage bay for the left-turn lane is 100 feet (30 meters) long.

Signal System Configuration

The signal system consisted of three intersections with equal distance (links) between intersections. The approaches or links are 2,640 feet long or approximately ½ mile spacings (800 meters). The signal spacing provides good progression, thus limiting platoon dispersion. Turn bays, when used are 100 feet (30 meters) long, with storage capacity for approximately four to five cars. The turn bays have adequate transition and storage capacity, not inhibiting the flow of vehicles on the through lanes. The signal system in Figure 4-4 is a series of nodes that represent intersections or entry points. The system has entry nodes denoted by 8XXX from which the NETSIM model generates vehicles. "Dummy" nodes (1-3, 20, 24, and 41-43) are used to identify the approach links and link lengths. The dummy nodes have no control and thus have no impact on the traffic flow in the system. Traffic signals provide control at the three intersections represented by nodes 21, 22, and 23. These intersections or nodes are the focal point of the operational analysis.

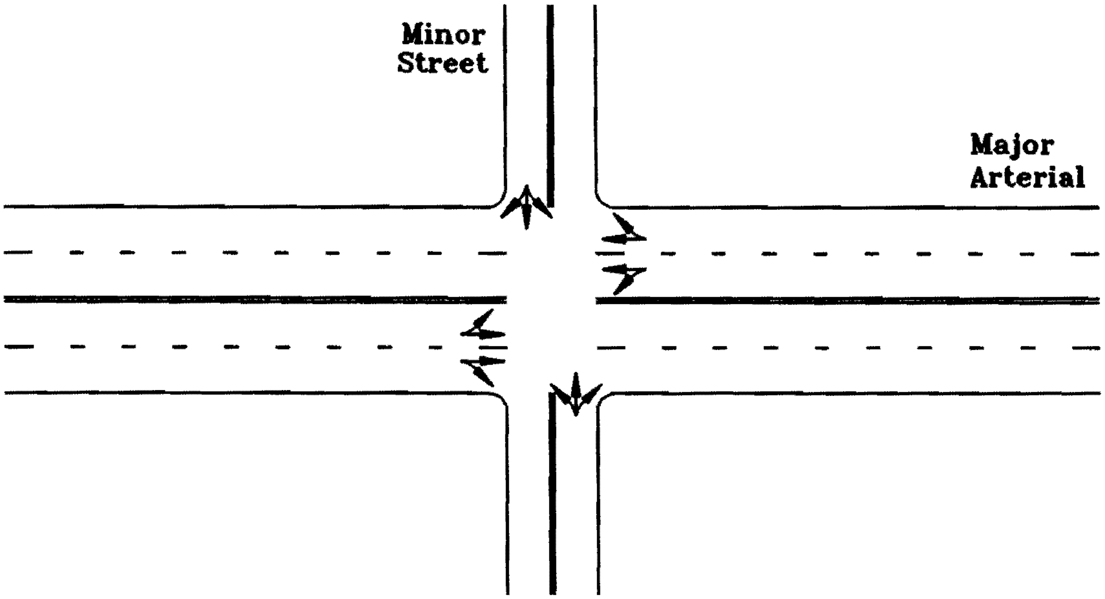


Typical 5x4 Geometric Configuration

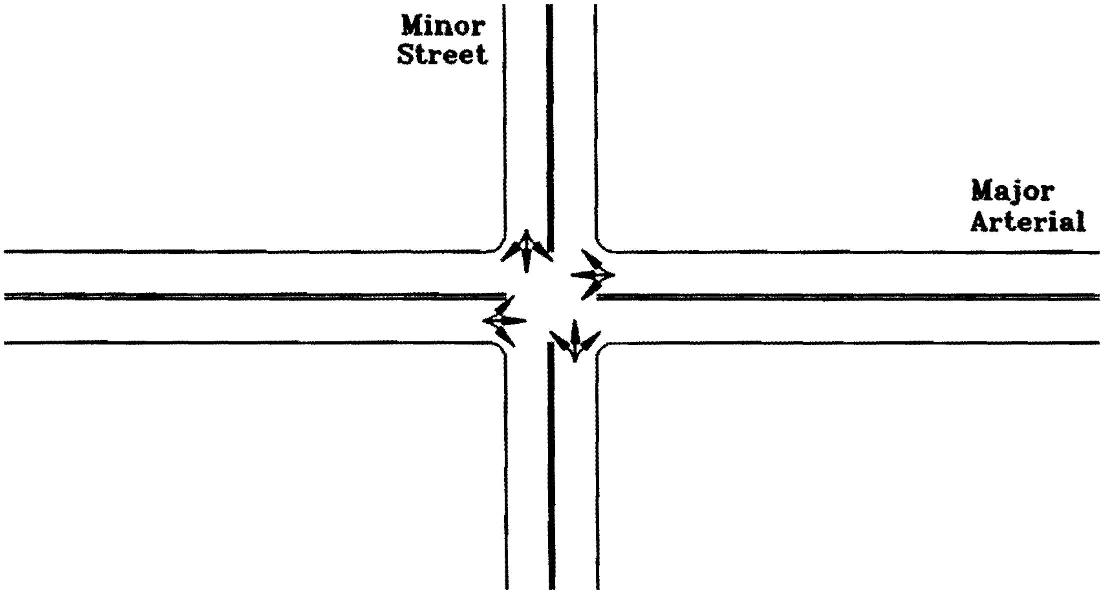


Typical 5x2 Geometric Configuration

Figure 4-2. 5×4 and 5×2 Geometric Configuration



Typical 4x2 Geometric Configuration



Typical 2x2 Geometric Configuration

Figure 4-3. 4×2 and 2×2 Geometric Configuration

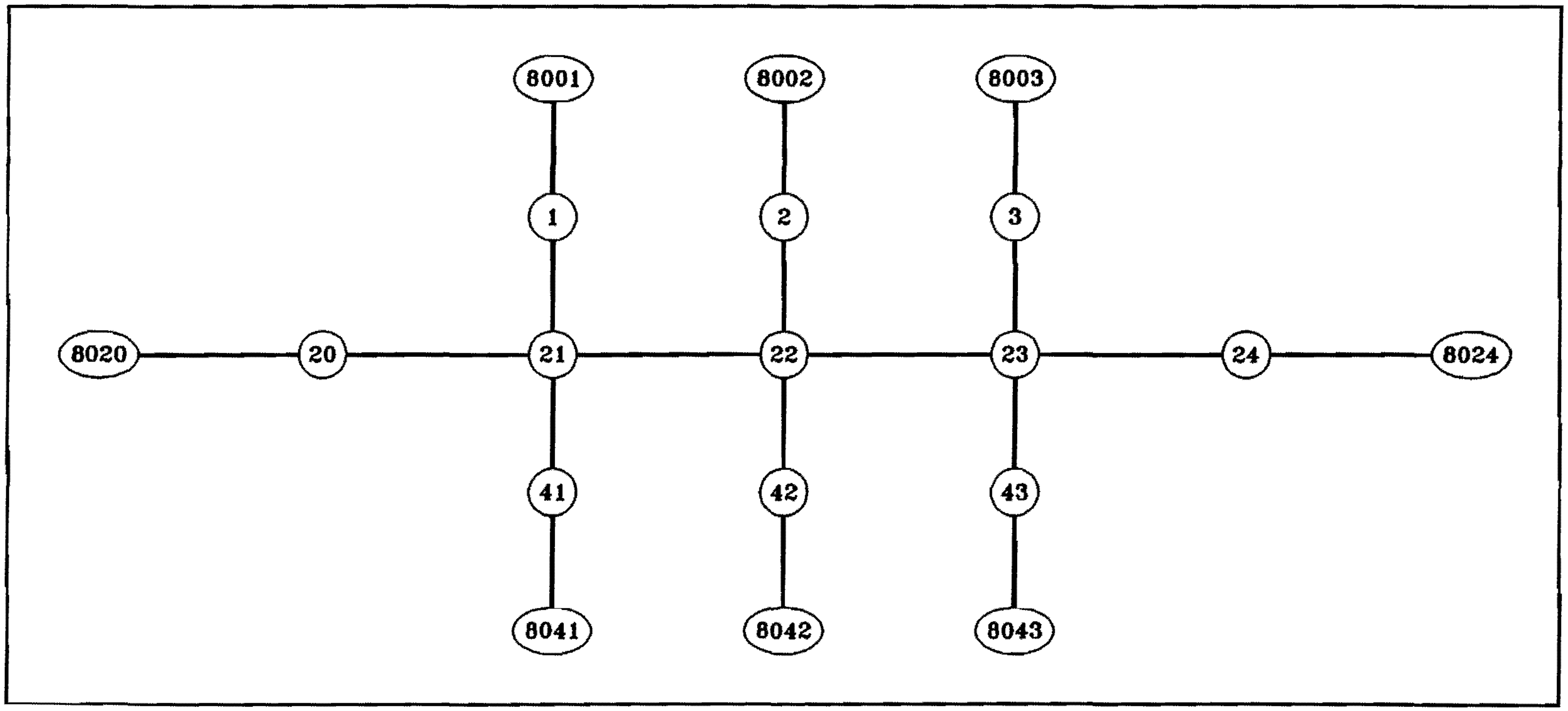


Figure 4-4. Netsim Node Network Configuration

A range of traffic volumes were simulated to provide the most benefit to the practicing traffic engineer. In addition, the assorted traffic volumes contributed to establishing a clear trend in delay. The approach traffic volumes that were simulated are shown in Table 4-5. These volumes represent approach volumes. Therefore, the highest bi-directional major street volume was 1,000 vph. These volume combinations represented volumes up to and including the volumes for signal warrants 1 and 2. This was done so that the relationship could be examined over a range of volumes that would be inclusive of the warranting volumes.

Table 4-5. Simulated Traffic Volumes Scenarios

		Major Street Approach Volumes (vph)								
		500	250	125	100	75	50	25	15	10
Minor Street Approach Volumes (vph)	500	✓								
	250	✓	✓							
	125	✓	✓	✓						
	100	✓	✓	✓	✓					
	75	✓	✓	✓	✓	✓				
	50	✓	✓	✓	✓	✓	✓			
	25	✓	✓	✓	✓	✓	✓	✓		
	15	✓	✓	✓	✓	✓	✓	✓	✓	
	10	✓	✓	✓	✓	✓	✓	✓	✓	✓

The composition of the traffic stream is 5 percent trucks and 95 percent autos. Turning movements were kept to a minimum so that delay would be a factor of the signal operation and not due to turning vehicles. The number of turning vehicles (right and left) were each set at 10 percent of the total approach volume. Directional distribution was assumed to be a 50/50 split.

Travel Speed

Travel speed on the major and minor streets was based on the number of approach lanes. As shown in Table 4-6, a street with 5 lanes was set at 40 mph (65 km/h), a street with 4 lanes was set at 35 mph (55 km/h), and a two lane street was set at 30 mph (50 km/h).

Table 4-6. Travel Speed on Major and Minor Street

Geometric Configuration	Posted Speed Limit - mph (km/h)	
	Major Street	Minor Street
5×4	40 (65 km/h)	35 (55 km/h)
5×2	40 (65 km/h)	30 (50 km/h)
4×2	35 (55 km/h)	30 (50 km/h)
2×2	30 (50 km/h)	30 (50 km/h)

Signal Timing Considerations

The signal timing parameters used in a signal simulation have a tremendous impact on the simulation results. Flashing signal operation does not require any timing parameters. However, in order to obtain a valid comparison to flashing operation, appropriate signal timings must be used for normal operation. There are many different factors which influence the selection of signal timing parameters. In this simulation, an attempt was made to select representative timings for the phasing, cycle length, pretimed phase splits, actuated timings, and signal system offsets. The following paragraphs describe the general philosophies that were used to select the signal timings for the simulations.

Phasing

Traffic signal phasing was determined based upon the geometric configuration. For the 5×4 and 5×2 geometric configurations which included an exclusive left-turn lane, a three-phase leading-left phasing operation was used. For the 4×2 and 2×2 geometric configuration, the analysis used the two-phase operation.

Cycle Length

The cycle length was determined from Webster's minimum delay cycle length equation (39). This method is dependent on the number of phases, the traffic volume in the intersection, and the saturation flow rate of each lane. Because of the extremely low traffic volumes, the cycle length determined by Webster's formula was usually short, in some cases as low as 20 to 25 seconds. To stay consistent with typical practice, 40 seconds was selected as the minimum cycle length for all simulations.

Pretimed Phase Splits

For pretimed signal operation, adequate pedestrian crossing time must be provided for all through movements. During typical periods of the day, the pedestrian crossing time is often less than the time needed to service vehicular demand. However, during low-volume periods, the pedestrian crossing time is typically longer than the time needed to satisfy vehicular demand. As a result, the pedestrian crossing time became the controlling factor in the calculation of the phase splits for this simulation. All pretimed signal timings in the simulations provided adequate pedestrian crossing time for the through phases.

Phase splits for a pretimed signal are typically calculated by proportioning the minimum delay cycle length to each phase according to the critical volumes. However, the minimum delay cycle length was usually smaller than the 40 second minimum used in the simulations. Therefore, the pretimed phase splits were determined from the pedestrian crossing times. The remaining time from the 40 second cycle was then assigned to the major street through phase. Change intervals were calculated using typical practices to eliminate the dilemma zone. The change interval included both yellow (three seconds) and all-red (one second) intervals.

Actuated Timings

Actuated signal control provides the ability to adjust signal operation according to the demands of traffic. For these simulations, fully actuated control was used. This included actuated control of pedestrian movements and the ability to skip phases. The actuated simulation assumed that pedestrians would be infrequent during the late-night and early-morning periods; therefore, a pedestrian phase was not included in the simulation.

The minimum green was ten seconds for major movements and three seconds for minor movements. The extension time was three seconds. The maximum green for each phase was based on the critical traffic volume for the phase.

Signal System Offsets

In a signal system, the offset is used to provide progression between signals on an arterial. The offset time was calculated from node 21 through node 23, as shown in Figure 4-4. Because the spacing between the signals was a constant ½ mile (800 meters) between all signals, the offsets for a given speed were also the same. For a 40 second cycle and a speed of 40 mph (65 km/h), the offset between intersections was 5.0 seconds; for 35 mph (55 km/h), it was 11.4 seconds; and for 30 mph (50 km/h), it was 20.0 seconds.

Simulation Methodology

For each type of signal control, simulations were performed for most combinations of major and minor street volumes, as shown in Table 4-5. It was not necessary to simulate all 45 different scenarios shown in Table 4-5 to identify trends. In most cases, 30 different volume scenarios were simulated.

As mentioned previously, the simulation models are stochastic; therefore, multiple simulations were made for each volume scenario. The averaged delays were then plotted as a function of the major-to-minor street volume ratio. Figure 4-5 is an example of a plot for yellow/red flashing operation before the data points were averaged. As illustrated in Figure 4-5, each simulation is represented by a different point on the graph. For any given combination of major street volume and volume ratio, there are several closely spaced points. These points represent the results of the stochastic simulations, which have some random variation in the volumes and delays. The initial delays and volumes were averaged to provide a single delay value for each combination of traffic volumes. Similar simulations were then performed for the other types of signal control (red/red flash, pretimed, and actuated operation).

Results of Operational Analysis

Total delay per vehicle (seconds/vehicle) was used as the measure-of-effectiveness for the operational analysis. The basic relationship between flashing and non-flashing signal operation is presented first using the results of the isolated intersection simulation. The total intersection delay per vehicle encompasses the delay experienced from vehicles on both the major and minor

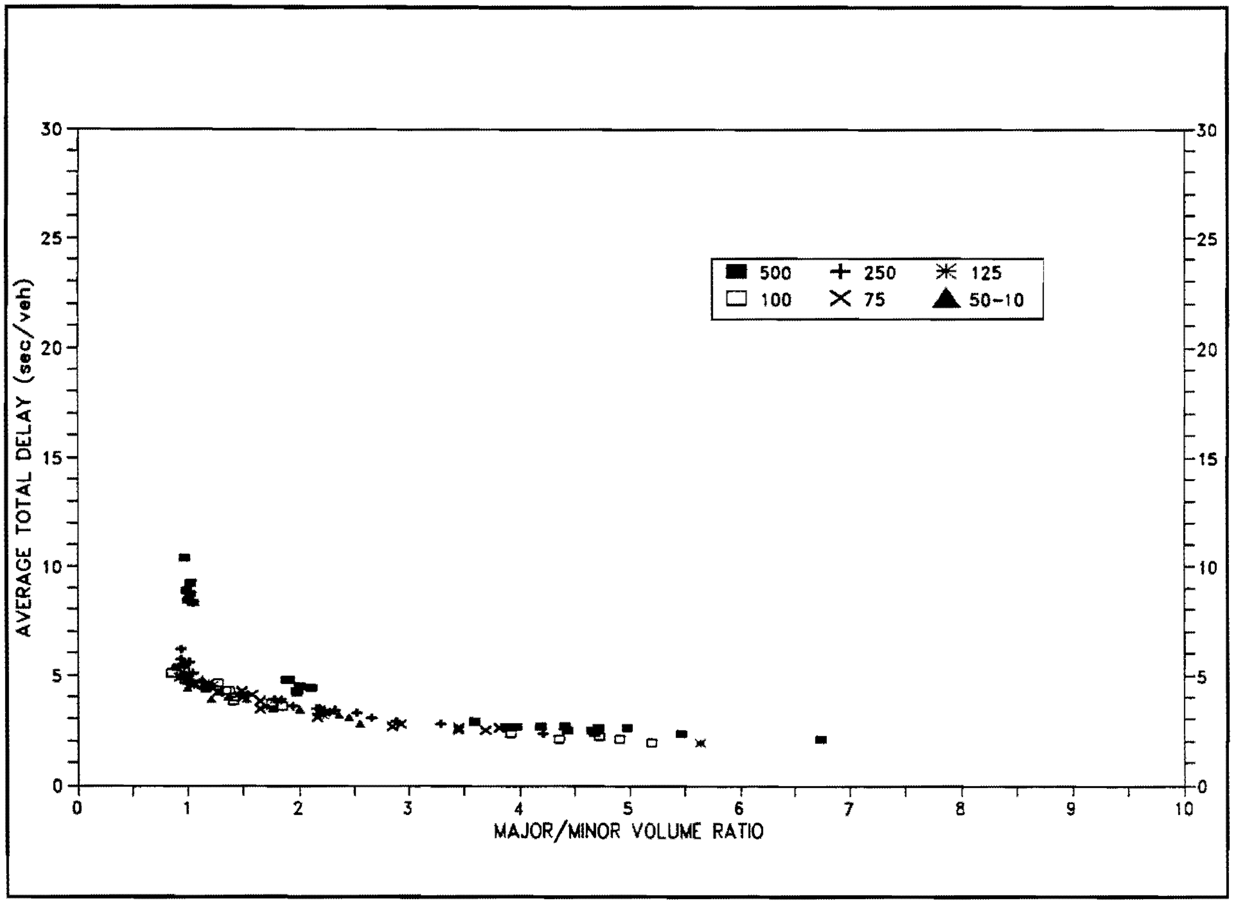


Figure 4-5. TEXAS Model Simulation of an Isolated Intersection - Yellow/Red Flashing Operation

street. Next, the results of the signal system simulation are presented. Because arterial progression on the major street was a major concern, the results for the signal system are presented showing the vehicle delay on the major street. Simulation results showing total intersection delay per vehicle as presented for the isolated intersection are presented in the appendices. The operational results of the diamond interchange evaluation are described separately at the end of the chapter.

Although the simulation strives to replicate "real world" conditions the computer models do have limitations. The simulation analysis assumes that perfect compliance to traffic control devices. That is, all drivers abide by the traffic control devices. As noted previously in the behavioral study this is not always the case. Some violation of traffic control devices does occur. The number of stops and delay presented in this chapter may be overestimated. Field estimate of stops and delays were not investigated in this study.

Isolated Intersection Analysis

Both the TEXAS and NETSIM models were used to simulate the signal operation at an isolated intersection. The results from the two models are basically similar. However, because NETSIM cannot analyze red/red flashing operation, the discussion of the isolated intersection analysis is based on the results of the TEXAS Model simulation. The results of the NETSIM simulations for many signal operations at an isolated intersection are contained in appendices.

The results were plotted by intersection geometric configuration and type of signal operation. For example, one graph would represent a 5×4 intersection operating with flashing yellow/red control. This single graph would illustrate all volume scenarios and/or combinations. Typically, the results were identified by the major street traffic volume. Each graph illustrates the total delay for the intersection. Trends in delay are identifiable for major street traffic volumes of: 500, 250, 125, 100, 75, and 10 to 50 vph. The lower traffic volumes of 10 to 50 vph were grouped together because of the similar delay results.

The results of this analysis are interesting. Generally, the delay for pretimed signals is the greatest, followed by red/red flash, actuated, and then yellow/red flash. Figures 4-6 and 4-7 graphically illustrate the comparison of the four signal operations using the 5×4 geometric configuration. Figure 4-6 represents major street traffic volumes of 250 to 500 vph, whereas Figure 4-7 represents major street traffic volumes of 125 vph and less. In comparing the pretimed to yellow/red flash (the two extremes), there is approximately a 65 to 75 percent difference in delay. The following sections of this report contain more detailed discussions of the simulation results by signal operation and geometric configuration.

Red/Red Flashing Operation at an Isolated Intersection

Red/red flashing signal operation requires that every vehicle on all four approaches come to a complete stop before proceeding through the intersection. Therefore, it is expected that the delay for red/red flashing operation will be high compared to other modes of signal operation.

The delay for red/red flashing operation for major street traffic volumes of 250 vph and less were typically 8 to 13 seconds per vehicle (spv) for all geometric configurations. For traffic volumes of 500 vph, and all geometric configurations except the 2×2, the delay for red/red flashing operation was typically 10 to 14 seconds when the volume ratio was two or more. For

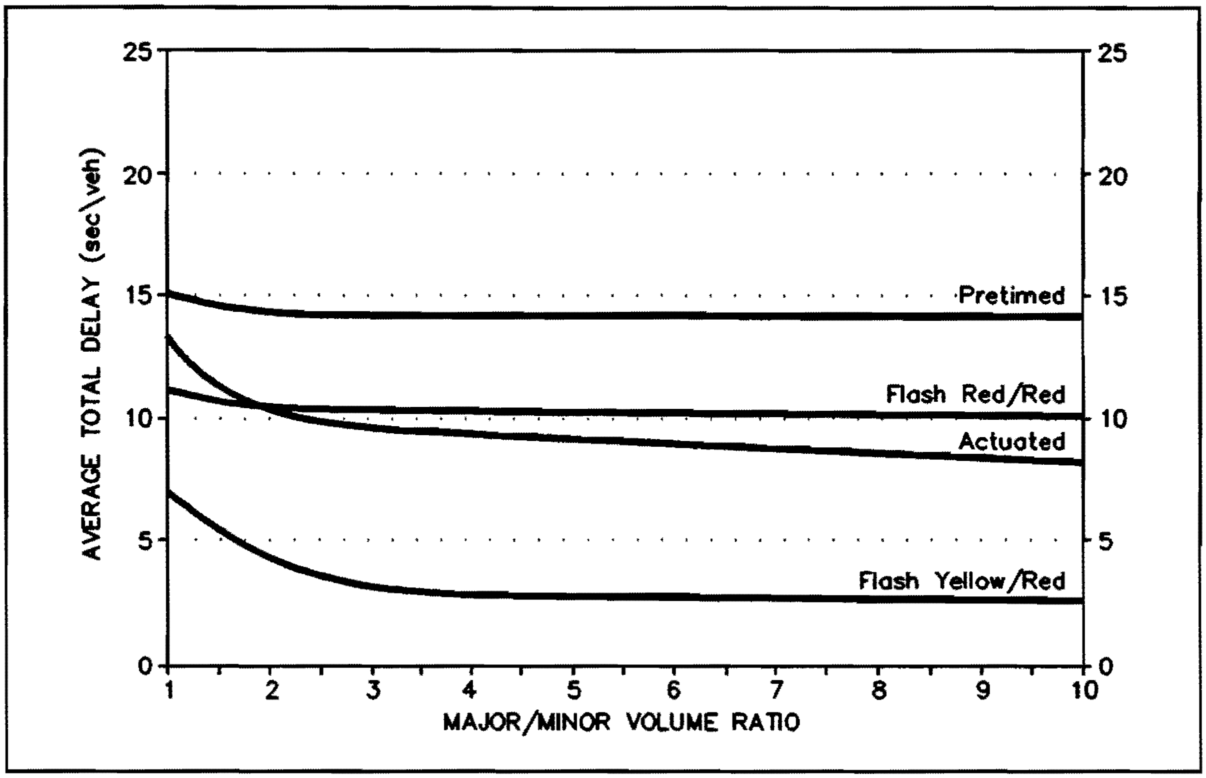


Figure 4-6. 5×4 Isolated Intersection - Major Street Approach Volume 250 to 500 vph

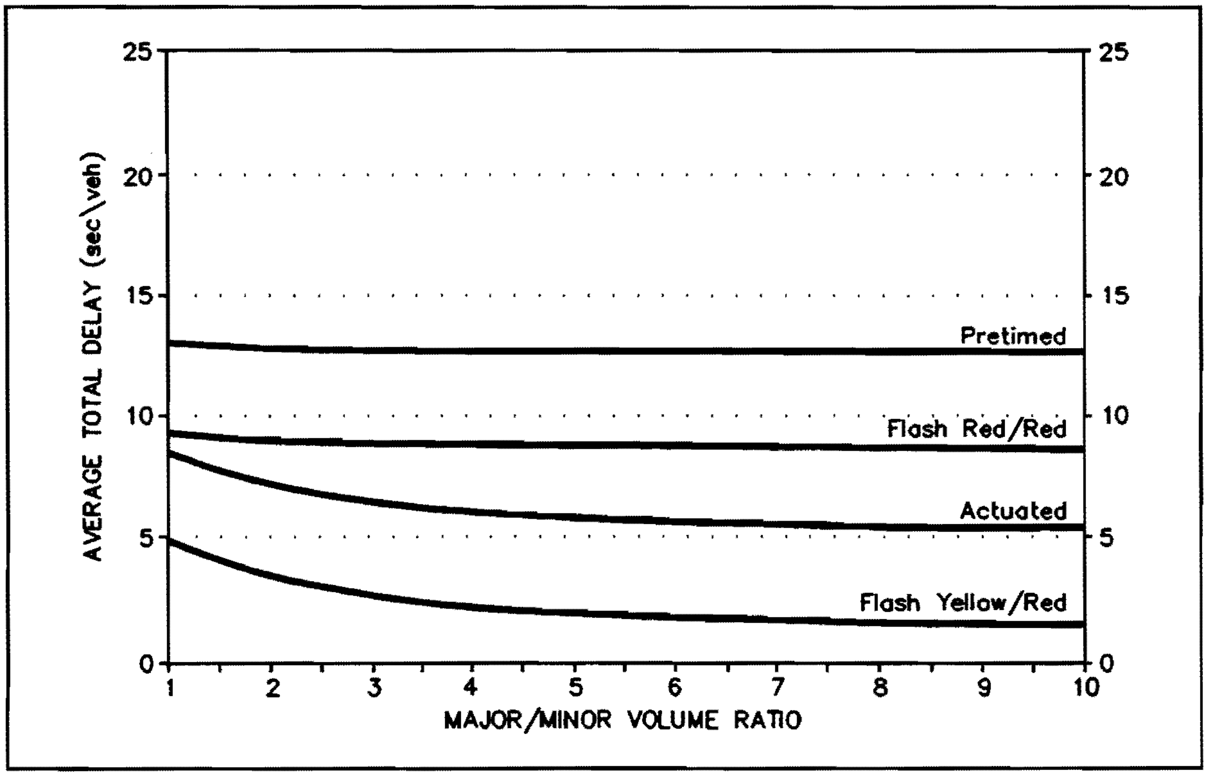


Figure 4-7. 5×4 Isolated Intersection - Major Street Approach Volume less than 125 vph

traffic volumes of 500 vph for the 2×2 geometric configuration, the delay for red/red flashing operation was greater than 30 spv. For the 5×2 and 4×2 geometric configuration, the delay for red/red flashing operation was also greater than 30 spv at a volume ratio of one. A definite trend can be depicted for a reduction in capacity. For example, at traffic volumes of 500 vph on the major street, the delay per vehicle is approximately 11 to 13 seconds, whereas delay for the 5×2 intersection is approximately 13 to 15 seconds (except at a volume ratio of one, where delay is greater than 30 seconds for all volume ratios for the 2×2). Although it is not practical to compare delay as a result of a reduction in capacity, this trend is important to recognize because the model performs in an expected manner. This trend validates the model's simulated delay results and thus promotes confidence in the model's results.

The delay for red/red flashing operation typically followed three identifiable patterns, each relative to the traffic volume on the major street. The three distinct trends follow the 500, 250, and 10-125 vph volume categories. These trends indicates that red/red flashing operation is somewhat influenced by traffic volume.

Table 4-7 summarizes the results of the analysis. Figures G-1 through G-4 in Appendix G are graphical representations of delay by geometric configuration and signal operation. Delay values greater than 30 spv were considered excessively high. Delay values above 30 spv were found to be associated with intersections with signal operations that did not adequately satisfy the traffic demand. The value of 30 spv was chosen arbitrarily as being a high delay value. In Table 4-7 and all subsequent tables and figures that illustrate delay, only delay values below 30 spv are shown.

Yellow/Red Flashing Operation at an Isolated Intersection

Yellow/red flashing operation requires vehicles on the minor street to make a complete stop and proceed into the intersection only when it is safe to do so. When traffic volumes on the major street are high, there may be few acceptable gaps for the vehicles on the minor street to merge into. Therefore, the delay imposed on the vehicles on the minor street would be expected to be high. On the other hand, when traffic volumes on the major street are low, there are more acceptable gaps for the minor street vehicles to merge into, and the delay is less. The delay on the major street is low because these vehicles are not required to stop. Most delay on the major street is caused by left and right turning traffic.

Table 4-7. Summary of Total Delay for Red/Red Flashing Operation at Isolated Intersections

Major Traffic Volume	Geometric Configuration	Volume Ratio					
		1	2	3	4	5	10
500 vph	5×4	12.5	11.5	11.0	11.0	11.0	10.5
	5×2	>30	14.0	13.0	12.5	12.5	12.5
	4×2	>30	12.0>	11.0	11.0	11.0	11.0
	2×2	>30	30	>30	>30	>30	>30
250 vph	5×4	10.0	9.5	9.5	9.5	9.0	9.0
	5×2	13.0	11.0	10.5	10.5	10.5	10.5
	4×2	11.5	10.0	9.0	9.0	9.0	9.0
	2×2	13.0	12.5	12.5	12.5	12.5	12.5
10 to 125 vph	5×4	9.0	9.0	8.5	8.5	8.5	8.0
	5×2	10.5	10.0	9.5	9.5	9.5	9.5
	4×2	9.5	8.5	8.0	8.0	8.0	8.0
	2×2	9.0	9.0	9.0	9.0	9.0	9.0

As shown previously in Figures 4-6 and 4-7, the delay for yellow/red flashing operation generally produces the least amount of total delay. For all geometric configurations and volume ratios greater than two, the delay for yellow/red flashing operation is approximately 10 spv. As the volume ratio approaches one, the delay for yellow/red flashing operation increases. On three geometric configurations, as traffic volume on the major street approaches 500 vph, the delay for the yellow/red flashing operation increases asymptotically as the volume ratio approaches one. This indicates that yellow/red flashing operation is not appropriate at intersections with high volumes where the major and minor street volumes are about equal.

Table 4-8 summarizes the delay for yellow/red flashing operation for all geometric configurations. Figures G-5 through G-8 graphically illustrate the delay associated with yellow/red flashing operation for all geometric configurations.

Comparing the delay for yellow/red flashing operation to the delay for red/red flashing operation indicates that the same general trend is present for both operations. Yellow/red flashing operation follows three distinct patterns representative of traffic volumes. The three patterns follow the 500, 250, and 10 to 125 vph traffic volumes. For the 2×2 geometric configuration, the delay for yellow/red flashing operation is substantially below the delay for the red/red flashing operation. Where the delay from red/red flashing operation for the 2×2 was above 30 spv, the delay for yellow/red flashing operation is 3 to 10 seconds for volume ratios greater than two. However, the delay for the 2×2 geometric configuration at a volume ratio of one is still above 30 spv. This indicates that yellow/red flashing operation is more appropriate for geometric configurations with lower capacity.

Table 4-8. Summary of Total Delay for Yellow/Red Flashing Operation at Isolated Intersections

Major Street Traffic Volume	Geometric Configuration	Volume Ratio					
		1	2	3	4	5	10
500 vph	5×4	9.0	4.5	3.0	2.5	2.5	2.0
	5×2	>30	7.0	4.0	3.0	2.5	2.0
	4×2	>30	8.0	4.5	4.0	2.5	2.0
	2×2	>30	10.0	6.0	4.5	4.0	3.0
250 vph	5×4	5.5	4.0	3.0	2.5	2.0	2.0
	5×2	8.5	4.5	3.0	2.5	2.0	2.0
	4×2	9.0	4.5	3.0	2.5	2.0	1.5
	2×2	9.0	4.5	3.5	3.0	2.5	2.0
10 to 125 vph	5×4	5.0	3.0	2.5	2.5	2.0	2.0
	5×2	6.0	3.0	2.5	2.5	2.0	2.0
	4×2	6.0	3.5	3.0	2.5	2.0	1.5
	2×2	6.0	3.5	3.0	2.5	2.0	1.5

Pretimed Operation at an Isolated Intersection

Pretimed signal operation repeats the same signal timings for every phase. Therefore, the delay associated with pretimed operation is significantly affected by the signal timings. In order to provide a true comparison of the delay associated with pretimed operation, the signal timings were optimized for each combination of major and minor street traffic volumes. While it is not common to develop signal timings for pretimed signals based on nighttime volumes, the optimized timing is indicative of the lowest level of delay that would exist for a pretimed signal. However, the lowest cycle length for the signal timings was 40 seconds, and all signal timings included accommodation of pedestrian crossing times.

The data indicates that the geometric configuration has a big impact on the delay. The delay associated with the larger intersections has a much smaller variance between volume ratios of one to ten. The smaller intersections show a much greater variance in delay. This is graphically illustrated in Figures G-9 through G-12. It is important to remember that the phasing is different for the five-lane intersections with an exclusive left-turn lane and the other intersections without a left-turn lane. In Figure G-9, the delay for the 5×4 intersection is represented by a flatter line. In Figure G-12, which represents delay for the 2×2 intersection, the line representing delay has a much greater slope for the same range of volume ratios. Table 4-9 summarizes the delay for pretimed operation for all geometric configurations.

Table 4-9. Summary of Total Delay for Pretimed Operation at Isolated Intersections

Major Street Traffic Volume	Geometric Configuration	Volume Ratio					
		1	2	3	4	5	10
500 vph	5×4	17.0	15.5	15.5	15.5	15.0	15.0
	5×2	>30	15.5	15.5	15.0	14.0	14.5
	4×2	23.5	11.5	10.0	9.0	8.5	8.5
	2×2	>30	20.5	15.0	12.5	11.5	9.5
250 vph	5×4	13.0	12.5	12.5	12.0	12.0	12.0
	5×2	13.0	12.0	12.0	12.0	11.5	11.5
	4×2	11.5	10.0	8.5	7.5	7.0	7.0
	2×2	14.0	11.0	9.0	8.5	8.5	7.5
125 vph	5×4	12.0	12.0	12.0	12.0	12.0	12.0
	5×2	12.0	11.5	11.0	11.0	11.0	11.0
	4×2	10.5	8.5	7.5	7.0	6.5	6.5
	2×2	11.0	9.5	8.0	8.0	7.5	6.5
100 - 75 vph	5×4	12.0	12.0	12.0	12.0	12.0	12.0
	5×2	11.0	10.5	10.5	10.5	10.5	10.5
	4×2	9.0	7.5	7.0	6.5	6.5	6.5
	2×2	9.0	7.5	7.0	6.5	6.0	6.0
50 - 10 vph	5×4	12.0	12.0	12.0	12.0	12.0	12.0
	5×2	10.5	9.5	9.5	9.5	9.5	9.5
	4×2	9.0	7.5	7.0	6.5	6.5	6.5
	2×2	9.0	7.5	7.0	6.5	6.0	6.0

A comparison can be made between delay for pretimed and for flashing operation. For the larger geometric configuration (i.e., 5×4 and 5×2), the delay for the pretimed operation is higher than the delay for red/red flashing operation and much higher than the delay for yellow/red flashing operation. For the 5×4 intersection, the delay for red/red flashing operation is between 8 and 12 spv, whereas for the pretimed operation with the same geometric configuration, the delay is 12 to 17 spv.

The delay for pretimed and red/red flashing operation decreases as the geometric configuration begins to get smaller. Delay for the 5×2 intersection with traffic volume of 500 vph on the major street is in the range of approximately 15 seconds for the pretimed operation, as compared to 12 to 15 seconds for the red/red flashing operation.

Actuated Operation at an Isolated Intersection

Actuated signal operation is variable, adjusting to the traffic demands at the intersection. The length of a phase is determined by the actuations on the approach detectors. When there is no traffic, then some phases can be skipped. Because of this ability to adjust to traffic demand, actuated operation has less delay as compared to pretimed signal operation. The TEXAS Model used in the simulation will skip phases when no vehicles are detected. However, because the TEXAS Model does not possess the Memory-On or Memory-Off feature, a phase will be called even when a vehicle enters the detector and then leaves before the phase is served. Therefore, the delay values produced for the actuated operation are slightly higher than results representative of a controller with the Memory-On or Memory-Off feature. The values are only slightly higher because of the low percentage of turning traffic volumes.

The delay associated with actuated control is generally greater than that for yellow/red or red/red flashing operation, but less than that for pretimed. The delay resulting for actuated operation is consistently two to three seconds less than the delay for pretimed operation for major street volumes less than 125 vph. However, for major street volumes of 250 vph, the delay for actuated control is approximately the same as the delay for pretimed. Table 4-10 summarizes the delay for actuated operation for all geometric configurations. Figures G-13 through G-16 graphically illustrate delay for actuated signal operation for all geometric configuration.

Summary of Isolated Intersection Analysis

Based on the operational analysis of the four most basic signal operations, it is apparent that the red/red and yellow/red flashing operation can reduce delay compared to normal operation. In every case studied, the delay for yellow/red flashing operation was the lowest, and the delay for red/red flashing operation was highest for the smaller intersections (less available capacity). For the larger intersections (i.e., 5×4 and 5×2), delay for pretimed operation was higher than for red/red flashing operation. Table 4-11 provides a comparison of each operation for volume ratios greater than three. This comparison was based on the delay for each signal operation contained in Figures G-1 through G-16, and Tables 4-7 through 4-10. For each geometric configuration and signal operation, the relative position remained unchanged for volume ratios greater than three. For volume ratios less than three, the relative position of each signal operation changed. Table 4-12 provides a comparison of each signal operation for a volume ratio of one. By comparing the two tables, it can be seen that the relative position of the delay curves change. For example, for the 4×2 geometric configuration, red/red flashing operation has the most delay for volume ratios between three and ten, whereas pretimed operation has the most delay for a volume ratio of one. Figures G-17 through G-28 graphically illustrate the comparison for the four types of signal control for all geometric configuration.

Table 4-10. Summary of Total Delay for Actuated Operation at Isolated Intersections

Major Street Traffic Volume	Geometric Configuration	Volume Ratio					
		1	2	3	4	5	10
500 vph	5×4	20.5	14.5	12.0	11.0	10.5	10.0
	5×2	28.0	15.5	13.0	12.0	11.5	10.0
	4×2	20.0	12.0	10.0	10.0	9.5	9.5
	2×2	>30	>30	>30	23.5	18.5	8.5
250 vph	5×4	13.5	11.5	10.2	9.5	9.0	9.0
	5×2	12.5	10.0	8.5	8.0	7.5	7.5
	4×2	11.0	8.5	7.5	7.0	6.5	6.5
	2×2	15.5	10.5	8.0	6.5	5.5	4.0
125 vph	5×4	11.5	9.0	7.5	7.0	7.0	7.0
	5×2	9.0	6.5	5.0	4.5	4.5	4.0
	4×2	8.5	6.0	5.0	4.0	3.5	3.0
	2×2	8.5	5.5	4.5	3.0	2.0	2.0
100 - 75 vph	5×4	10.0	8.5	7.5	7.0	7.0	7.0
	5×2	9.0	6.5	5.0	4.5	4.5	4.0
	4×2	7.0	5.0	4.0	3.5	3.0	2.5
	2×2	6.0	4.0	2.5	2.0	2.0	2.0
50 - 10 vph	5×4	8.0	7.5	7.0	7.0	7.0	7.0
	5×2	6.0	5.0	4.0	4.0	4.0	4.0
	4×2	4.5	3.5	3.0	2.5	2.0	2.0
	2×2	4.0	3.0	2.5	2.0	2.0	2.0

Table 4-11. Comparison of Signal Operation for Volume Ratios of Three to Ten at Isolated Intersections

Major Street Traffic Volume	Geometric Configuration	Red/Red Operation	Yellow/Red Operation	Pretimed Operation	Actuated Operation
500	5×4	#3	#1	#4	#2
250		#3	#1	#4	#2
100-125		#3	#1	#4	#2
10-75		#3	#1	#4	#2
500	5×2	#3	#1	#4	#2
250		#3	#1	#4	#2
100-125		#3	#1	#4	#2
10-75		#3	#1	#4	#2
500	4×2	#4	#1	Tie	Tie
250		#4	#1	#3	#2
100-125		#4	#1	#3	#2
10-75		#4	#1	#3	#2
500	2×2	#4	#1	#2	#3
250		#4	#1	#3	#2
100-125		#4	Tie	#3	Tie
10-75		#4	Tie	#3	Tie

Notes: Comparison was made from Tables 4-7 through 4-10.
#1 = Lowest delay, #4 = Most delay.
Tie = Approximately the same amount of delay.

Table 4-12. Comparison of Signal Operation for a Volume Ratio of One at Isolated Intersections

Major Street Traffic Volume	Geometric Configuration	Red/Red Operation	Yellow/Red Operation	Pretimed Operation	Actuated Operation
500	5×4	#2	#1	#4	Tie
250		#2	#1	#4	#3
100-125		Tie	#1	#4	Tie
10-75		Tie	#1	#4	Tie
500	5×2	#2	#1	#4	#3
250		#3	#1	#4	#2
100-125		#3	#1	#4	#2
10-75		#3	#1	#4	#2
500	4×2	#4	#3	#2	#1
250		Tie	#1	Tie	#2
100-125		#3	#1	#4	#2
10-75		#3	#1	#4	#2
500	2×2	#4	#1	#2	#3
250		#2	#1	#3	#4
100-125		#3	#1	#4	#2
10-75		#3	Tie	#4	Tie

Notes: [1]Comparison was made from Tables 4-7 through 4-10.
#1 = Lowest delay, #4 = Most delay.
Tie = Approximately the same amount of delay.

Signal System Analysis

The signal system was analyzed using the NETSIM model, as the TEXAS Model cannot model more than one intersection. As was found in the isolated intersection analysis, the system analysis showed a clear relationship between the volume ratio and total delay.

The results of the signal system are presented differently from those of the isolated intersection analysis. As indicated previously, arterial progression was provided in the pretimed and actuated signal timings in an effort to minimize delay on the major street. Because major street progression was a primary consideration of the signal system, the analysis evaluates only the delay for the major street. However, the total network delay results are presented in the appendices for comparison to the isolated intersection results.

The results of the signal system generally followed the relationships found in the isolated intersection analysis. The delay for pretimed signal operation is the highest, followed by actuated, and then yellow/red flashing operation. Figures 4-8 and 4-9 graphically illustrate total delay for the three signal operations. Figure 4-8 represents traffic volumes on the major street of 250 and 500 vph, whereas Figure 4-9 represents traffic volumes on the major street of 10 to 125 vph. Comparing the pretimed to the yellow/red flashing operation (the two extremes), there is approximately a 65 percent difference in delay on the major street. These two figures are presented to give a generalized summary of the results. A more detailed discussion of the results are presented in the following paragraphs.

Red/Red Flashing Operation in a Signal System

It was stated previously that the NETSIM model cannot simulate red/red flashing operation; therefore, no simulations were performed for red/red flashing operation as part of a signal system. However, it seems unlikely that red/red flashing operation would be used in a signal system; therefore, the inability to simulate this case is not significant.

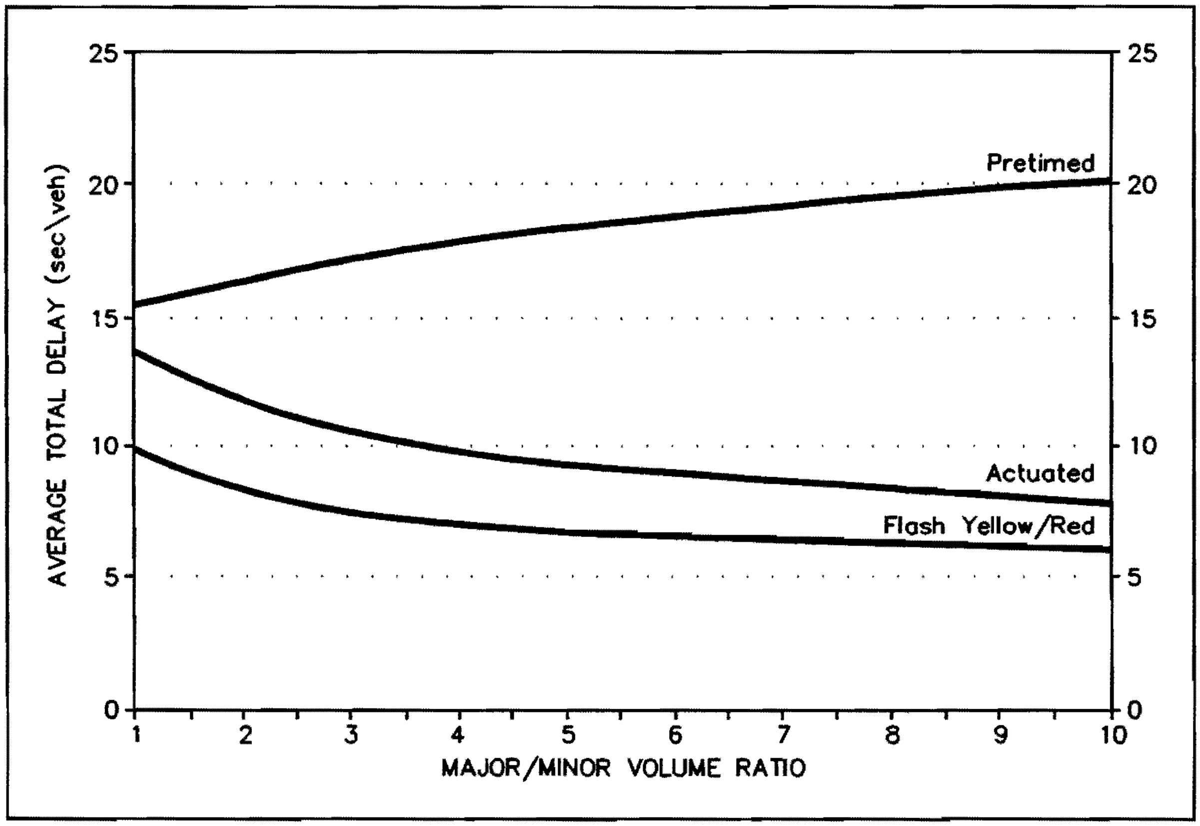


Figure 4-8. 5×4 Signal System - Major Street Approach Volume 250 to 500 vph

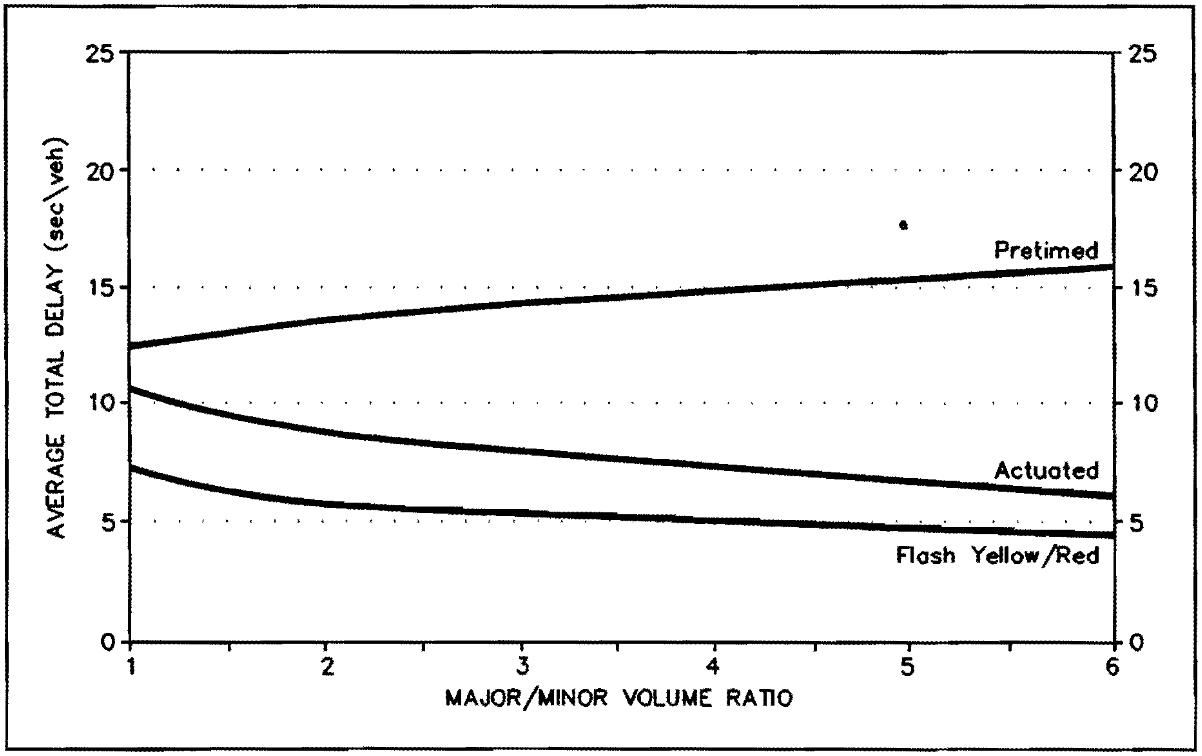


Figure 4-9. 5×4 Signal System - Major Street Approach Volume 10 to 125 vph

Yellow/Red Flashing Operation in a Signal System

The primary advantage of yellow/red flashing operation in a signal system is that vehicles on the major street are not required to stop. In effect, a continuous green progression band is provided for the major street traffic. The signal system delay for the yellow/red flashing operation was evaluated based on the major street delay. Figure 4-10 illustrates the major street delay for the 5×4 geometric configuration and the relationship of the flashing operation as a function of major and minor traffic volumes.

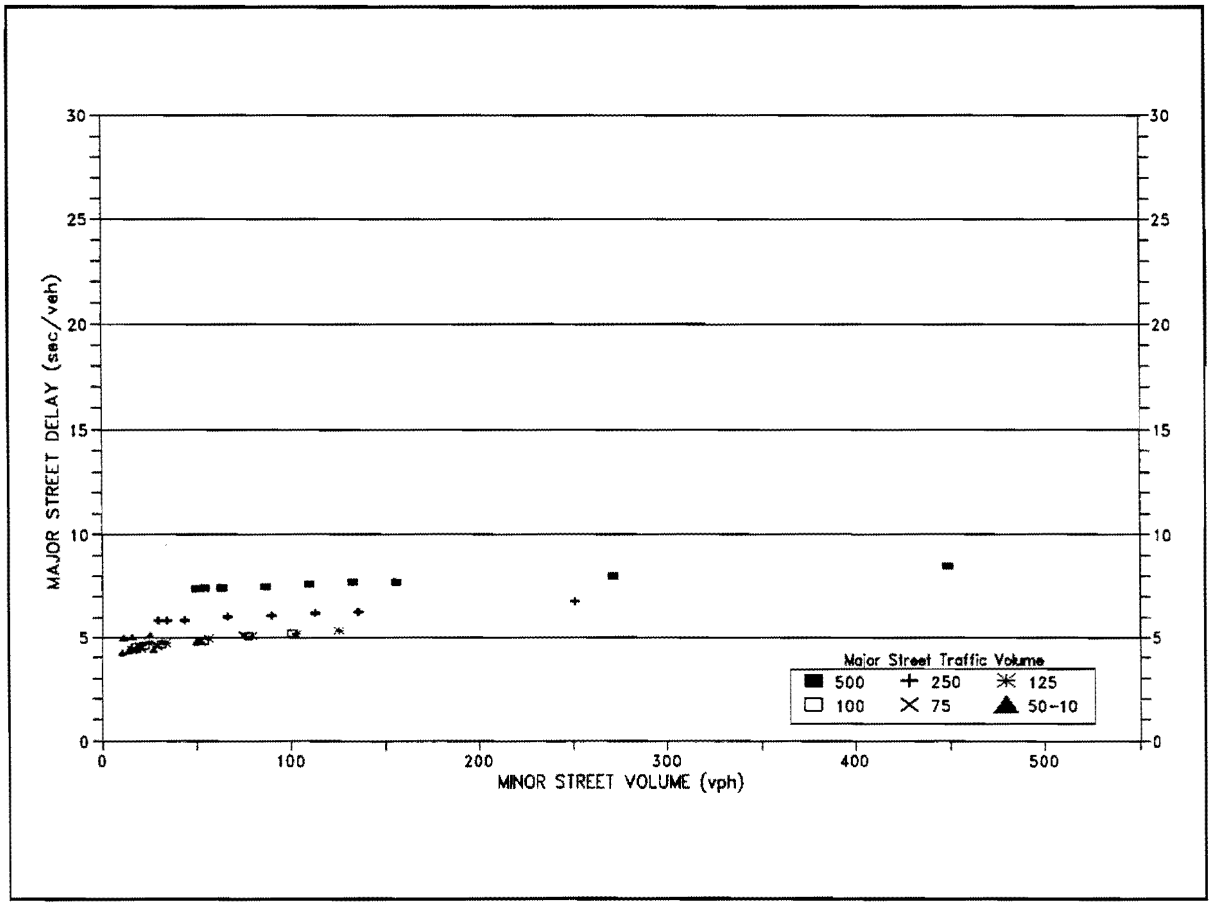


Figure 4-10. 5×4 Signal System- Yellow/Red Flash

As Figure 4-10 shows, the delay for the major street with 500 vph and a minor street traffic volume range between 50 and 500 is approximately 7.5 to 8.5 spv. And the major street delay for 10 to 125 vph on the major street is approximately 4.0 to 5.5 spv. The major street delay for the 5×2, 4×2, and 2×2 geometric configurations resembled the results shown for the 5×4 geometric configuration. The 5×2 and 4×2 geometric configurations showed major street delay values very close to those of the 5×4 configuration. However, because the 2×2 geometric configuration has the least amount of capacity, the 2×2 showed approximately 2 to 3 seconds more delay than the other configurations. The major street delay for yellow/red flashing operation for all geometric configurations is shown in Table 4-13 and graphically illustrated in Figures G-29 through G-32.

Table 4-13. Summary of Major Street Delay for Yellow/Red Flashing Operation in a System

Major Street Traffic Volume	Geometric Configuration	Minor Street Volumes						
		25	50	100	150	200	250	500
500	5×4	7.5	7.5	7.5	8.0	8.0	8.0	9.0
	5×2	7.5	7.5	7.5	8.0	8.0	8.0	9.0
	4×2	7.5	7.5	8.0	8.0	8.0	8.5	9.0
	2×2	11.0	11.0	11.5	12.0	12.0	12.0	13.0
250	5×4	6.0	6.0	6.5	7.0	7.0	7.0	—
	5×2	6.0	6.0	6.0	6.5	6.5	7.0	—
	4×2	6.0	6.0	6.0	6.5	6.5	7.0	—
	2×2	8.0	8.0	8.5	8.5	9.0	9.0	—
10-125	5×4	4.5	4.5	5.0	—	—	—	—
	5×2	4.5	5.0	5.0	—	—	—	—
	4×2	4.5	5.0	5.0	—	—	—	—
	2×2	5.0	5.5	6.0	—	—	—	—

Pretimed Operation in a Signal System

Delay for pretimed signal operation was approximately twice the delay for yellow/red flashing operation. Because of the low traffic volumes, minimum pedestrian crossing time dictated signal operation. In other words, much of the green time was unused by vehicles because of the crossing time provided for pedestrian movements. The accommodation of pedestrian movements is required for pretimed signals, even though there may not be any pedestrian activity. This resulted in higher delay than if pedestrian crossing time had not been provided. The normal trend of major street delay is proportional to the amount of traffic on both the major and minor street. This trend is evident in Figure 4-11. Figure 4-11 shows that for traffic volumes of 500 and 250 vph on the major street, and 500 and 250 vph on the minor street, the amount of major street delay is proportional to the amount of traffic. However, once the signal operation is dictated by the pedestrian movement time, the major street delay becomes a constant value. For example, in Figure 4-11, for major street traffic volume of 500 vph and minor street traffic volume between 50 and 250 vph, the major street delay is approximately 23 spv. For the same major street volume and 250 to 500 vph on the minor street, the delay is proportional to the amount of minor street traffic; major street delay is approximately 28 spv at 500 vph on the minor street.

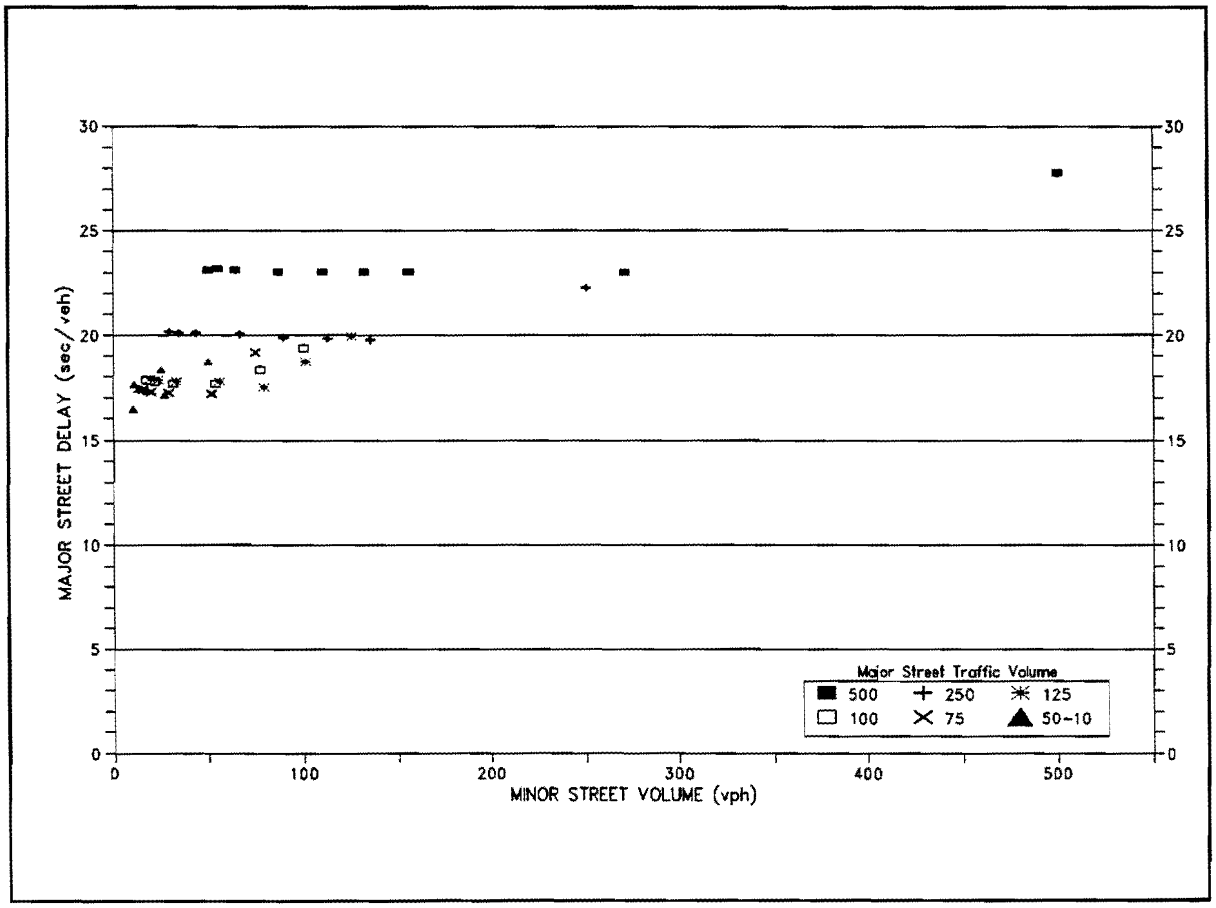


Figure 4-11. 5×2 Signal System - Pretimed Operation

Table 4-14 summarizes the major street delay for pretimed signal system operation. Figures G-33 through G-36 graphically illustrate the major street delay for the 5×4, 5×2, 4×2, and the 2×2 geometric configuration, respectively. For the larger intersections, the delay is higher compared to that of the smaller intersections. From the figures in the appendix, it can be inferred that the smaller the intersection, the lower the major street delay. This can be attributed to the number of lanes the pedestrian has to cross. Because the graphs represent delay on the major street, the delay is reflective of minor street environment. In other words, the delay on the major street is influenced by the amount of vehicle traffic on the minor street and accommodation of pedestrians to cross the minor street. It is normal for pedestrian signals to allow pedestrians to cross the minor street when the major street is serving through vehicles.

Table 4-14. Summary of Major Street Delay for Pretimed Operation in a System

Major Street Volume	Geometric Configuration	Minor Street Volumes					
		50	100	150	200	250	500
500	5×4	23.0	23.0	23.0	23.0	22.5	22.5
	5×2	23.0	23.0	23.0	23.0	23.0	28.0
	4×2	16.0	16.0	16.0	17.0	18.5	29.5
	2×2	16.0	16.5	16.5	17.0	18.0	24.5
250	5×4	19.5	19.5	19.5	19.5	19.5	—
	5×2	20.0	20.0	20.0	21.0	22.0	—
	4×2	13.0	13.0	17.0	19.0	21.5	—
	2×2	11.5	12.0	15.0	18.0	20.5	—
10-125	5×4	17.0	17.0	—	—	—	—
	5×2	17.5	19.0	—	—	—	—
	4×2	13.0	17.0	—	—	—	—
	2×2	9.5	13.0	—	—	—	—

Actuated Operation in a Signal System

The major street delay for actuated operation was substantially lower than the delay for pretimed operation. Because phase skipping is permitted with fully-actuated control, undue delay was eliminated. It was previously noted in the discussion on actuated operation for isolated intersections that the version of the TEXAS Model used in this analysis did not have the Memory-On or Memory-Off feature, which is important in skipping phases and minimizing delay. The NETSIM model, used to simulate the signal system, does possess this feature; therefore, the delay is representative of a fully actuated signal control. Figure 4-12 illustrates the delay for the 5×4 geometric configuration. From Figure 4-12, it can be seen that major street delay is approximately 5 spv when volumes on the minor street are low. As the minor street volume increases, so does the major street delay. This increase can be attributed to the signal system serving increasing traffic on the minor street.

The geometric configuration had little influence on major street delay. The delay for actuated control for the 5×4 and 5×2 configurations is approximately the same. This is expected because the traffic signal timing was selected to provide arterial progression. A background cycle was used to limit the minor street green time to portions of the cycle which did not interfere with major street progression. Table 4-15 summarizes the major street delay for actuated signal system operation. Figures G-37 through G-40 graphically illustrate the major street delay for all geometric configurations.

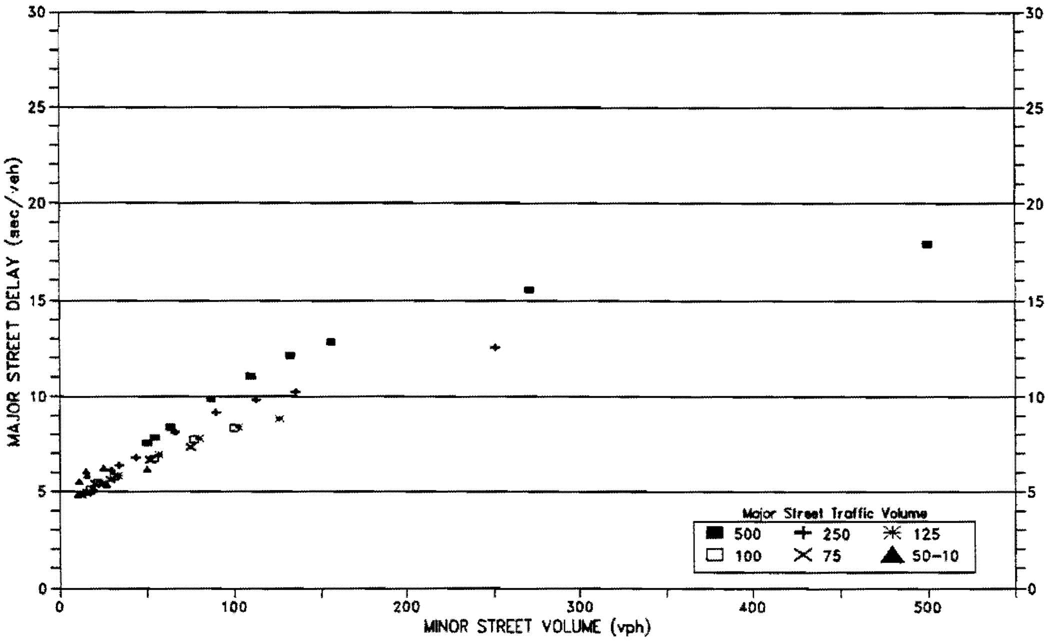


Figure 4-12. 5×4 Signal System - Actuated Operation

Table 4-15. Summary of Major Street Delay for Actuated Operation in a System

Major Street Traffic Volume	Geometric Configuration	Minor Street Volumes						
		25	50	100	150	200	250	500
500 vph	5×4	6.0	7.5	10.5	13.0	15.0	15.5	18.0
	5×2	6.0	8.0	11.0	13.0	14.5	16.0	22.0
	4×2	6.5	8.0	10.5	12.0	13.5	14.5	20.5
	2×2	18.0	18.0	18.0	18.0	18.0	18.0	26.5
250 vph	5×4	5.5	7.0	9.5	11.0	12.0	12.5	---
	5×2	5.5	7.0	9.5	11.0	12.5	14.0	---
	4×2	6.0	7.5	10.0	10.5	12.5	13.5	---
	2×2	13.0	13.0	13.0	13.0	14.0	16.0	---
10-125 vph	5×4	5.0	6.5	8.0	---	---	---	---
	5×2	5.5	6.5	8.5	---	---	---	---
	4×2	5.5	6.5	8.5	---	---	---	---
	2×2	9.0	9.0	9.5	---	---	---	---

Summary of Signal System Results

The following conclusions can be drawn from Tables 4-13 through 4-15 and Figures G-41 through G-52.

1. Yellow/red flashing operation produces the least amount of system delay, followed by actuated and pretimed signal operation.
2. The total intersection delay can be reduced by as much as one-third if pretimed operation is changed to actuated (coordinated) operation and reduced by approximately two-thirds if changed to yellow/red flashing operation.
3. The geometry of the signal system only affects the amount of delay; it does not affect the general trend of the curve.
4. The major street delay is affected very little by the type of geometry.

Conclusions from Isolated and Signal System Operational Analysis

No formal guidelines exist that suggest when it is appropriate to place a signal in the flashing mode of operation (emergency flash excluded). However, the literature review identified several studies containing recommendations indicating when flashing signal operation is favored over normal operation. The most comprehensive study on the operational aspects of flashing and normal signal operation was sponsored by the FHWA (6). The FHWA study developed an analytical model to predict stopped delay.

This study evaluated various types of signal operation using the TEXAS and NETSIM computer models for an isolated intersection and a three-intersection signal system. The results of the operational analysis compared favorably with the findings of the FHWA study. Specifically, this study agreed with the FHWA study on the following issues:

1. Yellow/red flashing operation produces less delay (overall versus stopped) than any other form of normal operation under all combinations of major and minor street volumes.
2. Red/red flashing operation produces less delay (overall versus stopped) than pretimed operation under most traffic volume combinations, even where signals are coordinated on an arterial.

3. Red/red flashing operation produces more delay (overall versus stopped) than actuated (coordinated or isolated) at most traffic volume ratios.

The inference that can be drawn from this analytical analysis is that yellow/red flashing operation should be used whenever possible, although there are a few exceptions to this rule. The actual traffic volume at which a change to yellow/red flashing operation is advantageous is somewhat arbitrary. In general, a volume ratio of about three is appropriate.

From the analysis, red/red and yellow/red flashing operation generally produced less delay than did other signal operations for traffic volumes that were more than approximately 50 percent of the MUTCD Volume Warrant, which is about 450 vph per approach. The analysis indicates that for traffic volumes greater than 500 vph per approach, both red/red and yellow/red flashing operation start to produce more or as much delay as most normal signal operations.

Circumstances in which it may be advantageous to use flashing operation from a delay standpoint are described in the following paragraphs.

Use of Red/Red Flashing Operation

Pretimed Operation. Red/red flashing operation reduces delay only for the larger intersection geometrics where pretimed operation is in use. Typically, red/red flashing operation can reduce delay when: the major street traffic is less than 50 percent of the MUTCD Volume Warrant (approximately 500 vph), the existing traffic signal control is pretimed operation, and the intersection is large (e.g., 5×4 or 5×2). Red/red flashing operation does not reduce delay for any of the scenarios where pretimed operation was the existing condition and the geometric configurations were small.

Actuated Operation. In general, there are no advantages in changing actuated operation to red/red flashing operation.

Use of Yellow/Red Flashing Operation

Pretimed Operation. Yellow/red flashing operation can reduce the total delay for any geometric configuration when traffic volumes are less than 50 percent of the MUTCD Volume Warrants. The amount of delay saved in changing to yellow/red flashing signal operation from pretimed operation ranged between 1/2 to 5/6. The exception to this is for 5×2 and 4×2 intersections with major street volumes greater than 250 vph and a volume ratio less than two. For those intersections, the delay from yellow/red flashing operation was more than the delay for the pretimed operation.

Actuated Operation. Yellow/red flashing operation can reduce the total delay when the geometric configurations is large (i.e., 5×4 and 5×2) and the traffic volume ratio is greater than three. Delay can be reduced by approximately 50 percent.

For the smaller intersection configurations and traffic volumes greater than 250 vph on the major street, the delay can be also be reduced by changing actuated to the yellow/red flashing operation. However, for those smaller geometric configurations, but with traffic volumes less than 125 vph on the major street, actuated and yellow/red flashing operation produce approximately the same amount of delay.

Diamond Interchange

Diamond interchanges are widely used in Texas in both urban and rural areas as a means of transferring freeway traffic to and from the surface street system. The type of signal control at diamond interchanges is normally dictated by traffic demand during daytime hours. During the nighttime, however, benefits may be gained by changing the signal operation from normal to flashing operation. The following section of the report describes previous research on traffic signal operation at diamond interchanges. Following the previous research section are the results of a traffic model simulation analysis for a diamond interchange using flashing and normal signal operation.

Previous Research

A literature search did not identify any previous research on flashing signal operation at diamond interchanges. However, research has been conducted by TTI on interconnected traffic signals at diamond interchanges which evaluated normal operation and STOP sign control (40).

The TTI study identified two primary types of traffic control at diamond interchanges: STOP signs and traffic signals. This research focused on identifying when it is appropriate to use either type of traffic control. Current practice at the time was to use the MUTCD warrants for signal installation. This practice was deemed partially incorrect because the Volume Warrants are based on traffic volumes at a single intersection. The TTI study (40) concluded that:

> *"The warrants do not adequately reflect the operational characteristics of diamond interchanges, nor are they sensitive to the traffic patterns between the two intersections at a diamond interchange. ... Therefore, it is necessary to develop clear and effective guidelines for installing all-way STOP signs versus traffic signals for control at diamond interchanges under varying traffic patterns and geometric characteristics."*

The TTI research compared all-way stop sign control with traffic signal control. To provide general guidelines for signal control, the signal operations studied included pretimed control, actuated control, three-phase operation, and four-phase operation with overlaps. The guidelines were based on two primary MOE's: the ratio of internal volume per lane to external volume per lane, and a composition of left-turning traffic and through-traffic within the internal stations.

The results of the TTI study found that shorter queues of vehicles were observed for STOP sign control than for signal control when interchange traffic volumes were low. As interchange traffic increased, longer queues were observed for STOP sign control than for signal control. The point where STOP sign control and signal control cross was approximately 1,100 vehicles per hour per lane (vphpl). The data showed that the proportion of left-turning traffic to internal traffic had very little effect on the suggested interchange volume guidelines for signalization. The suggested guidelines for installing traffic signals at diamond interchanges are presented in Table 4-16.

Table 4-16. Guidelines for Installing Traffic Signals at Diamond Interchanges

Ratio of Internal to External Traffic Volumes (per lane volumes)	Minimum Interchange Volume for Signal Control (per lane volumes)
0.4	1,050
0.5	950
0.6	850
0.7	750

Source: Reference (40)

Previous research on diamond interchange signal control indicates that normal operation is best used when traffic volumes reach the levels indicated in Table 4-16. All-way STOP sign control is a satisfactory traffic control device when traffic volumes are below the level indicated in Table 4-16. It can be inferred that red/red flashing signal operation is also an acceptable traffic control method when traffic volumes are below the levels indicated in Table 4-16. Normal operation should be used when traffic volumes are higher.

Diamond Interchange Simulation

For this analysis, a generic diamond interchange was simulated with low traffic volumes. Simulated traffic volumes on the frontage road and/or arterial ranged from 50 to 1,000 vph per approach. The diamond interchange was simulated using the TEXAS Model. Researchers at the University of Texas at Austin developed the TEXAS Model Version 3.0 (Diamond Interchanges) to perform detailed computer simulation capable of modelling all traffic movements through two closely-spaced at-grade intersections of the diamond interchange as well as the internal lanes between them.

Simulation Methodology

Two types of traffic control were simulated using the TEXAS Model for diamond interchanges: flashing and normal operation. "Figure 4" phasing was chosen to represent normal operation because it is one of the preferred phasing plans for most diamond interchanges in Texas. "Figure 4" phasing allows all traffic movements to proceed through the interior lanes of the interchange without additional stops when proper splits and offsets are selected. The

"Figure 4" pattern achieves progression within a wide range of traffic volumes. A total of ten detectors were located on all four external inbound approaches and both internal approaches. Figure 4-13 illustrates detector placement. Flashing signal operation was simulated with the arterial roadway receiving the flashing yellow indication, and the frontage road receiving the flashing red. The primary reason for this control strategy is that the freeway, by definition, would carry all through traffic; therefore, the frontage roads are merely transferring freeway traffic to the arterial, and there is no need for progression on the frontage road. The secondary reason for this type of control strategy is that diamond interchanges are, in many cases, in an isolated location; therefore, progression is not possible.

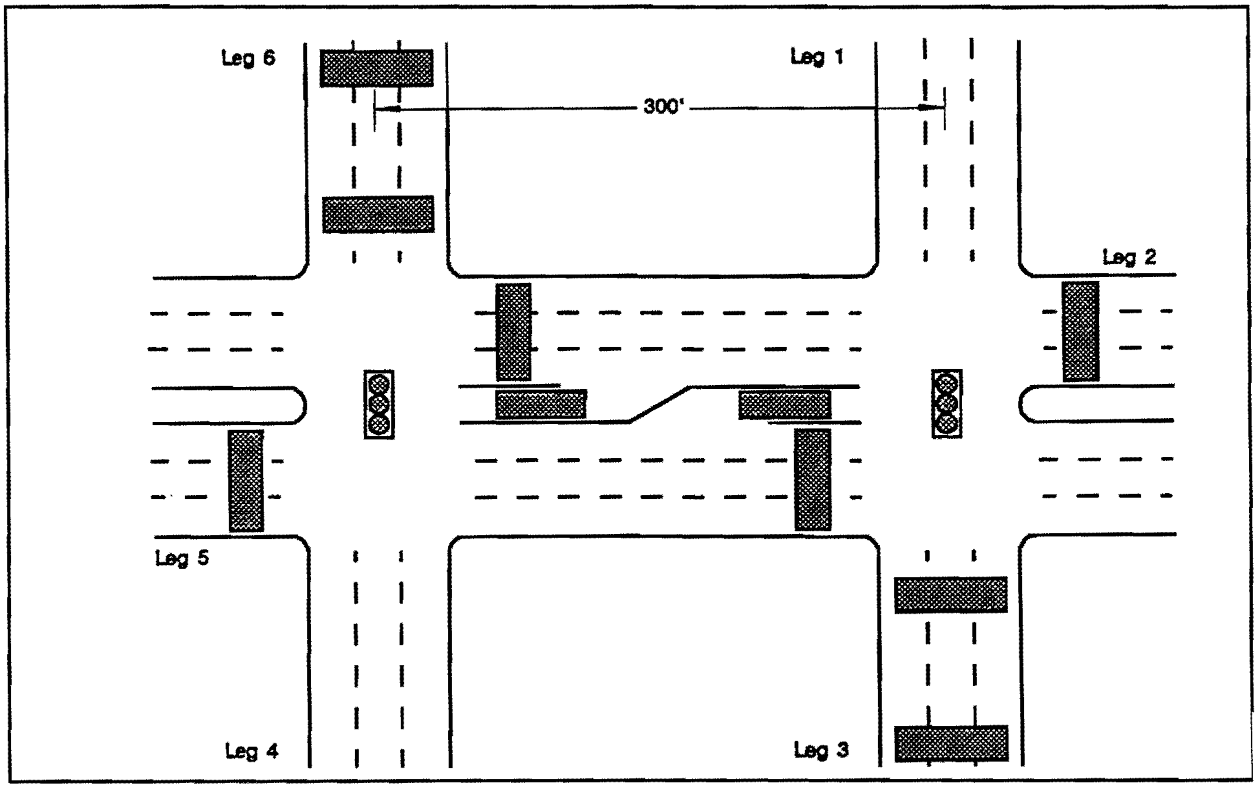


Figure 4-13. Geometric Configuration and Detector Layout for a Diamond Interchange

Because the TEXAS Model Version 3.0 (Diamond Interchanges) was developed specifically to model the diamond interchange, the majority of operational parameters called for in the software program were default values. However, the travel speed, travel movements by percent, and initial interval were changed. Table 4-17 lists the operational parameters used in the simulation.

Table 4-17. Operational Values Used To Model The Diamond Interchange

Description	Simulation Value
Distance between frontage roads	300 feet (90 meters)
Inbound lanes	Arterial = three lanes, Frontage Rd. = three lanes
Speed limits	Arterial = 40 mph (65 km/h), Frontage Rd. = 50 mph (80 km/h)
Turning movements:	
Left, throughs, and rights	33.3% each, (Arterial and Frontage Rd.)
U-turns	0 %
Normal Operation	"Figure 4" phasing arrangement
Initial interval	8 seconds
Vehicle interval	2 seconds
Yellow-change interval	3 seconds
All-red interval	1.0 seconds
Max extension	30 seconds
Clearance green for phases 3-5	5 seconds
Advance green for phases 1-7	7 seconds
Advance green for phases 2-6	7 seconds
Transfer gap for phase 2	3 seconds
Transfer gap for phase 7	3 seconds

A range of traffic volumes were simulated to determine if there was a particular volume in which one operation was better than the others. Traffic volumes (per approach) ranged from 50 to 1,000 vph on both the arterial and frontage roads. Because each approach has three lanes (refer to Table 4-17), the highest single lane volume used in the simulation was approximately 333 vphpl. The traffic volumes simulated are intentionally low to moderate; thus they represent a diamond interchange for which it may be questionable whether to implement flashing operation or remain in normal operation.

As discussed in earlier chapters, the TEXAS Model is a microscopic stochastic model. Therefore, to achieve a high level of comfort with the results, each volume scenario was run a minimum of five times, then averaged to determine one value to represent that specific volume scenario.

Results of Simulation

The data from the TEXAS Model were analyzed in a manner consistent with the previous analyses of four-legged intersections using overall total delay per vehicle as the chosen measure-of-effectiveness. Delay was analyzed for the four external approaches (leg 2, 3, 5 and 6 on

Figure 4-13). Only external approaches were analyzed to prevent "double counting" of vehicle stops and subsequent delay. This should not present any biased results because the "Figure 4" phasing operates such that there should be few vehicles stopped in the internal approaches. For flashing operation, the arterial receives the flashing yellow indication; therefore, there should be few vehicles in the internal approaches. The few vehicles delayed in the internal approaches would be left-turning vehicles. The data were arranged to produce graphs that relate total delay versus the ratio of arterial traffic volume to frontage road volume as a function of the arterial street volume. Six groups of arterial street volumes are used: 1,000, 750, 500, 250, 100, and 50 vph.

Normal Signal Operation at a Diamond Interchange

Normal operation featured a fully-actuated signal controller that served each approach based on vehicle demand. The "Figure 4" phasing arrangement is similar to a 4-phase signal operation, except there is no concurrent traffic flow. This is not to be confused with an overlap where two conflicting traffic flows both receive the green indication. Instead, the "Figure 4" phasing arrangement services each of the four primary directional movements one after another. The result is a safe and efficient signal operation.

The data from the normal operation show that as the volume ratio approaches unity, the delay increases exponentially. As illustrated in Figure 4-14, it is apparent that each volume group reaches its highest level of delay when there are equal traffic volumes on the arterial and frontage road. As the frontage road volume decreases, the ratio of arterial to frontage road volume increases.

Figure 4-14 also shows there is a level of traffic volume in which there is relatively constant delay. For example, for 750 vph on the arterial roadway with normal operation, the highest delay is approximately 53 spv at a volume ratio of one. At a volume ratio of three, there is approximately 33 seconds of delay per vehicle. And at a volume ratio of six, delay is still approximately 33 spv. This signifies that after frontage road traffic volume drops below a certain level, there is no effect on total intersection delay.

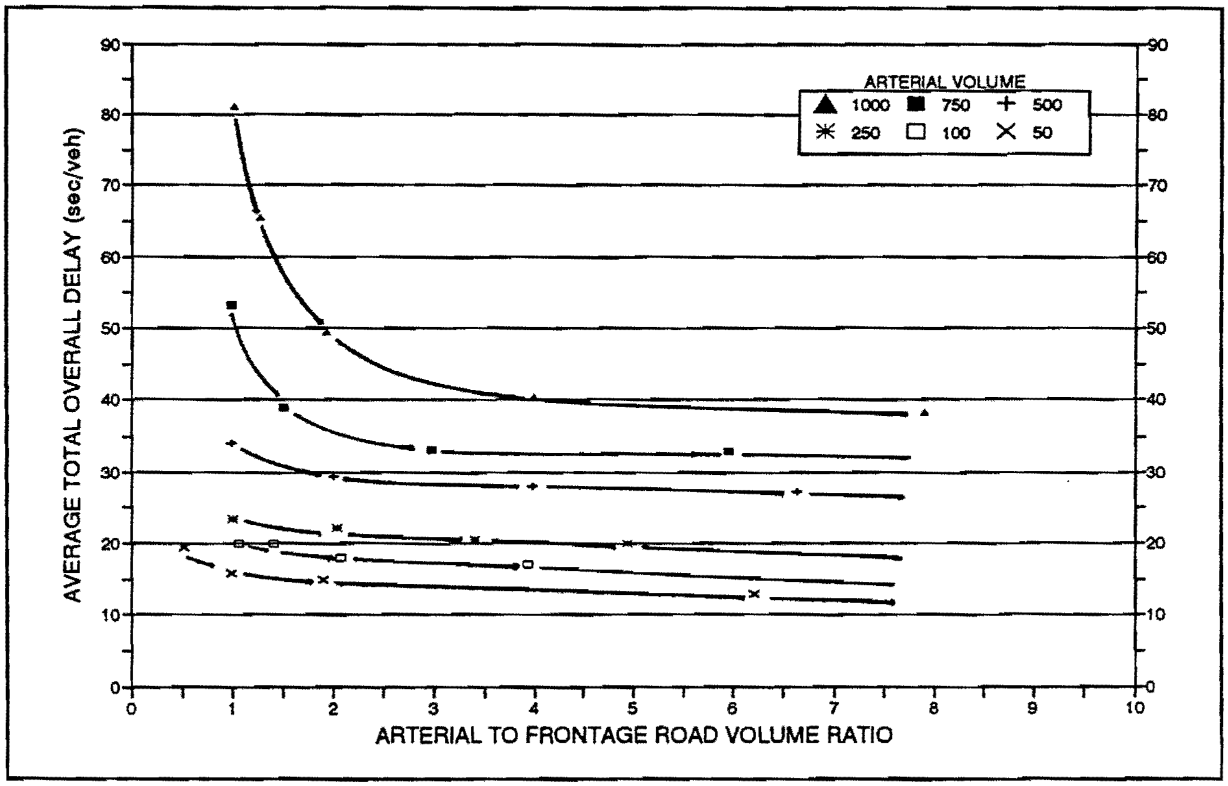


Figure 4-14. Texas Diamond Interchange - Non-Flashing Application

Flashing Operation at a Diamond Interchange

Flashing operation permitted the arterial movement to proceed through the interchange non-stop. The only delay that would have incurred would be the result of left-turning traffic. The data from flashing operation show a trend similar to that found with the normal operation. As shown in Figure 4-15, delay from flashing operation is highest when traffic volumes on the arterial and frontage roads are nearly equal. As the volume ratio increases, the total delay decreases. Figure 4-15 also shows that traffic volume groups less than 250 vph begin to represent approximately the same amount of delay. This is to say that delay becomes relatively constant for traffic volumes of 250 vph and less on the arterial roadway. This is because vehicles on the arterial roadway receive the yellow indication, and thus do not stop before entering the interchange.

Note that traffic volumes of 1,000 vph on the arterial are not shown for the flashing operation. For this condition, the TEXAS Model essentially fills both intersections with vehicles and cannot continue the simulation. This is not to say that the interchange cannot operate in flashing operation under this condition. Previous research by TTI (40) has shown that flashing operation can function with a higher volume, although long queues of vehicles are encountered.

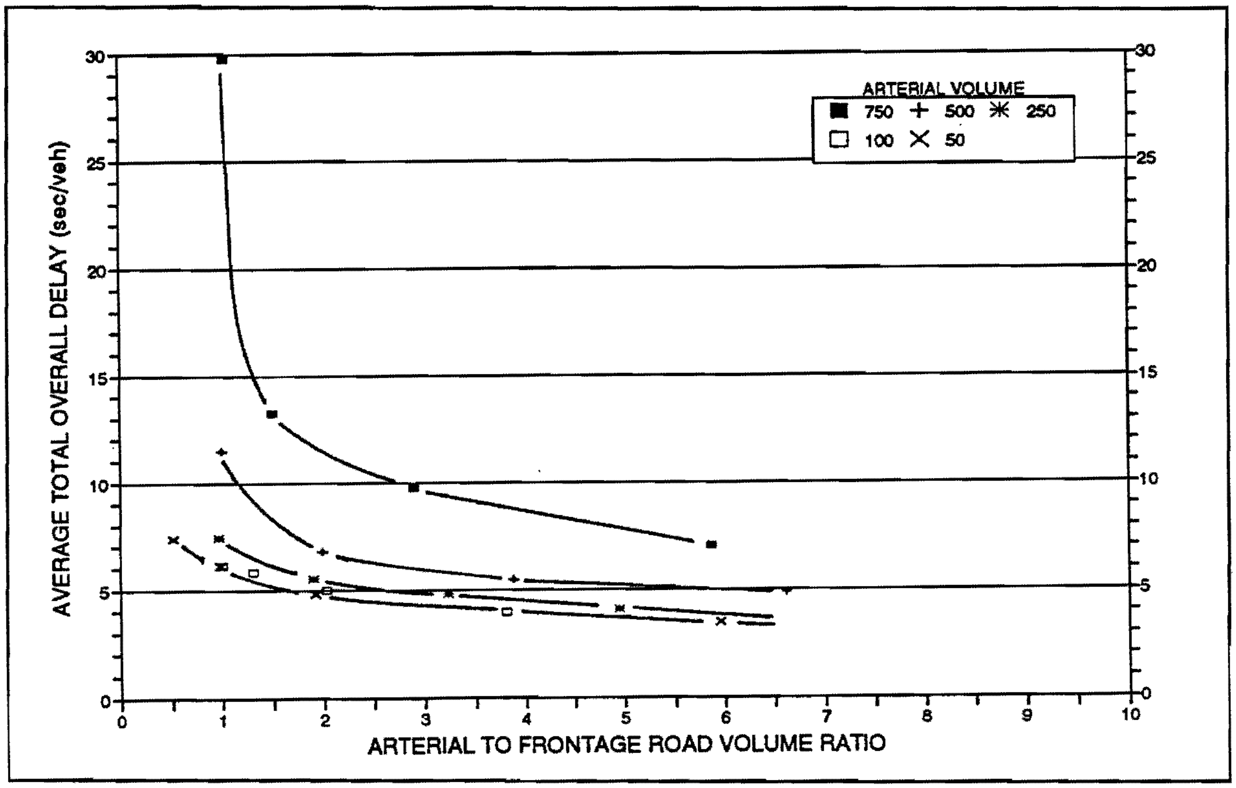


Figure 4-15. Texas Diamond Interchange - Total Overall Delay for Flashing Operation

Summary of Diamond Interchange Simulation Results

A comparison of Figures 4-14 and 4-15 indicates that, although the two have similar trends, there is no similarity in total delay. Delay can be reduced at least 50 percent by changing from normal signal control to flashing signal control. However, there is no evident point at which to make the change in signal control.

Conclusions and Recommendations

The operational analysis of diamond interchanges was evaluated by comparing flashing and normal signal operation, with normal operation using a "Figure 4" phasing arrangement. The results show a drastic difference in delay between flashing operation and normal operation. The difference between the flashing and normal operation would seem to indicate that, in terms of total delay, flashing signal control is a much better operational strategy for a diamond interchange when traffic volumes are low. The research indicated that flashing signal control reduced total delay by at least 50 percent.

The data did not support a distinction in delay between the normal and flashing signal operation other than that flashing operation produces much less delay. However, it is possible to correlate the guidelines found in Table 4-16 to the traffic volumes investigated in the simulation analysis to determine when normal signal operation can be changed to flashing operation. Because the guidelines in Table 4-16 are dependent on the number of vehicles per lane, Tables 4-18 and 4-19 represent a diamond interchange with three lanes and two lanes, respectively, on each approach. The number of vehicles in the internal movements were calculated using the assumed turning movements found in Table 4-17.

Table 4-18. Potential Implementation of Flashing Signal Operation at Diamond Interchanges with Three Approach Lanes

Arterial Traffic Volume	Frontage Road Traffic Volume	Arterial to Frontage Road Ratio	Ratio of Internal to External Traffic Volumes	Total Traffic Volume Entering Diamond Interchange	Signal Control
1,250	1,250	1.0	0.50	1,667	Signal
1,250	1,000	1.25	0.52	1,500	Signal
1,250	750	1.67	0.54	1,333	Signal
1,250	500	2.50	0.57	1,167	Signal
1,250	250	5.0	0.61	1,000	Flash
250	1,250	0.20	0.39	1,000	Flash
1,000	1,000	1.0	0.50	1,333	Signal
1,000	500	2.0	0.56	1,000	Signal
1,000	250	4.0	0.60	833	Flash
1,000	100	10.0	0.64	733	Flash
500	1,000	0.5	0.44	1,000	Signal/Flash
250	1,000	0.25	0.40	833	Flash
100	1,000	0.1	0.36	733	Flash
750	750	1.0	0.50	1,000	Flash
750	500	1.5	0.53	833	Flash
750	250	3.0	0.58	667	Flash
500	750	0.67	0.47	833	Flash
250	750	0.33	0.42	667	Flash
500	500	1.0	0.50	667	Flash
500	250	2.0	0.56	500	Flash
500	100	5.0	0.61	400	Flash
500	50	10.0	0.64	367	Flash
250	250	1.0	0.50	333	Flash
250	100	2.5	0.57	233	Flash
250	50	5.0	0.61	200	Flash
250	25	10.0	0.64	183	Flash

Note: Table 4-18 is based on TTI Research Report 344-1 (40) and theoretical arterial and frontage road volumes. The ratio of internal to external traffic volumes and total traffic volume are computed according to TTI Research Report 344-1. The type of signal control is dependent on guidelines found in Table 4-16.

Table 4-19. Potential Implementation of Flashing Signal Operation at Diamond Interchanges with Two Approach Lanes

Arterial Traffic Volume	Frontage Road Traffic Volume	Arterial to Frontage Road Ratio	Ratio of Internal to External Traffic Volumes	Total Traffic Volume Entering Diamond Interchange	Signal Control
1,250	1,250	1.0	0.50	2,500	Signal
1,250	1,000	1.25	0.52	2,250	Signal
1,250	750	1.67	0.54	2,000	Signal
1,250	500	2.50	0.57	1,750	Signal
1,250	250	5.0	0.61	1,500	Signal
250	1,250	0.20	0.39	1,500	Signal
1,000	1,000	1.0	0.50	2,000	Signal
1,000	500	2.0	0.56	1,500	Signal
1,000	250	4.0	0.60	1,250	Signal
1,000	100	10.0	0.64	1,100	Signal
500	1,000	0.5	0.44	1,500	Signal
250	1,000	0.25	0.40	1,250	Signal
100	1,000	0.1	0.36	1,100	Signal
750	750	1.0	0.50	1,500	Signal
750	500	1.5	0.53	1,250	Signal
750	250	3.0	0.58	1,000	Signal
500	750	0.67	0.47	1,250	Signal
250	750	0.33	0.42	1,000	Signal/Flash
500	500	1.0	0.50	1,000	Signal
500	250	2.0	0.56	750	Flash
500	100	5.0	0.61	600	Flash
500	50	10.0	0.64	550	Flash
250	250	1.0	0.50	500	Flash
250	100	2.5	0.57	350	Flash
250	50	5.0	0.61	300	Flash
250	25	10.0	0.64	275	Flash

Note: Table 4-19 is based on TTI Research Report 344-1 (40) and theoretical arterial and frontage road volumes. The ratio of internal to external traffic volumes and total traffic volume are computed according to TTI Research Report 344-1. The type of signal control is dependent on guidelines found in Table 4-16.

CHAPTER 5
ACCIDENT ANALYSIS

The relationship between accidents and flashing operation is another of the primary factors to be considered in a decision to implement flashing operation. The concern is whether the use of flashing operation during a portion of the day will cause an increase in accidents. This chapter describes an analysis of accidents which was performed to determine the safety implications of flashing signal operation. The objective of the analysis was to determine if accidents increased, decreased, or remained unchanged when normal signal operation was changed to flashing operation, or vice versa, particularly during nighttime, low-volume conditions. This chapter contains a critical review of previous research studies on flashing signal accidents and describes the accident analysis conducted as part of this study.

Literature Review

The literature review on accident analyses was first presented in Chapter 2 of this report. However, Chapter 2 was primarily focused on the warrants, guidelines, and/or recommendations as the result of previous research. In this section, the literature review evaluates the methodologies used in previous studies to investigate the relationships between accidents and flashing operation.

Washington, D.C. Study, 1966

The Washington, D.C. study (3) evaluated intersection accidents at selected intersections in the District of Columbia. Signal operation on ten arterial streets was changed from nighttime flashing to 24-hour normal (full-color) operation. Control intersections continued to use only flashing operation. It was believed that any variation of accident experience in the control group represented the effect of overall changes in conditions of the system (i.e. variations in traffic volumes, enforcement activities, etc.).

The study collected and analyzed accident data from 741 intersections. Based on the location and type of signal control, each intersection was placed into one of three distinct groups for analyses purposes. The three groups were:

- **Group I** - 162 signalized intersections which were converted from nighttime flashing operation to 24-hour normal operation.
- **Group II** - 177 signalized intersections not included in the conversion (from flashing to normal operation), but located no more than 2 blocks from the converted (Group I) signals. These intersections used flashing operation throughout the study period.
- **Group III** - 402 signalized intersections not included in the conversion, but located more than 2 blocks from the converted (Group I) signals. These intersections used flashing operation throughout the study period.

Accident data for flashing operation were collected for a five-month period between May and September in 1964. These data were then compared to accident data collected for the same five-month period in the following year, after the Group I signals were converted to normal operation. A statistical analysis of the accident frequencies was used to determine if there were significant changes in accident characteristics. The characteristics studied in each group were limited to: total number of accidents observed, number of angle collisions, number of personal injury accidents, and the number of property damage only accidents. Results from Groups I and II were compared with those for Group III.

The results indicated that Group I accidents showed a significant (at the 95 percent significance level) decrease in angle accidents when compared to Group III. Also, reductions occurred at the 90 percent confidence level for the following accident characteristics when compared with Group III: in frequency of angle accidents in Group II, in total accident frequencies for Groups I and II, and in the frequency of personal injury accidents in Group I. The study concluded that there was a 39.6 percent decrease in the total number of accidents for Group I when the signalized intersections were taken off flashing operation. It also revealed that there was a decrease in the severity of accidents for the same comparison.

The D.C. study results concluded that flashing operations contributed to increases in accidents. However, there were several areas of the study methodology that create equivocal results. Generally, studies of intersection accidents use a three- to four-year study period because it is commonly perceived that study periods shorter than three years do not provide adequate insight of accident trends. Accident trends develop over extended periods of time because such observations are random events. The expectancy of observing such events repeatedly is further decreased when brief time periods of the day are chosen for analysis, as is the case with all nighttime studies. Because traffic volumes during the night are generally lower than daytime volumes, not as many vehicles are exposed to conflicting maneuvers and the probability of observing an accident is further reduced. For these reasons, the five-month before-and-after study periods used in this evaluation may not accurately reflect accident trends.

To further confound the study results, the analysis was based on an aggregate evaluation of five different types of intersections. These intersection types consisted of four-leg, five-or-more leg, three-leg "T", three-leg "Y", and circle intersections. A review of the raw data collected revealed that the study did not distinguish between the different types of intersections when calculating the results. This is a source for erroneous conclusions since it is possible for one type of intersection to experience a higher or lower accident frequency. Hence, the aggregate accident trends based on all intersection types might be susceptible to large variations.

Marson's Thesis, Michigan State University, 1976

A Michigan State University thesis by Joseph Marson (5) compared accident data at 99 intersections with nighttime flashing operation to accident data at 70 intersections with 24-hour normal operation. Data were obtained from the Michigan Department of State Highways and Transportation (MDSHT) for 85 locations which used flashing operation and 63 locations with normal operation. The remaining 21 intersections (14 with flashing operation and 7 with normal operation) came from Macomb County Road Commission (MCRD).

Consecutive, two-year study periods were used to observe accidents over a four-year study period from 1968 to 1972. Using this methodology, two-year durations were sought for each flashing operation intersection to compare with a similar two-year duration for a normal operation intersection. Such a study design is commonly called a parallel comparative analysis because accident trends are reviewed for identical time periods using a control group and a treatment group. However, accident data for all of the MCRD locations and several of the MDSHT locations supported a shorter, 6- to 18-month study period for evaluation. It was not explicitly stated in the study how many intersections lacked the two-year study period.

Accident data were retrieved from a computer data base and from actual accident reports. Accidents were classified as intersection related and were included in the analysis if they occurred within 100 feet of the intersection. Accident rates for brief periods of the day were computed using fractions of the intersection Average Daily Traffic (ADT) and were based on the total number of vehicles entering the intersection during the hours of analysis. ADT counts on the major and minor street approaches were collected for the sites investigated. A majority of the state controlled intersections did not have minor street ADTs. For these locations the ratio of major to minor approach volume count was used to obtain the minor ADT. Total approach volumes were also used to estimate the intersection ADT for shorter time periods in the day.

A statistical analysis of daytime accidents was performed to confirm that all of the flashing and non-flashing locations were collected from the same population. The analysis used the mean accident rate calculated for daytime accidents occurring between the hours of 6:00 a.m. and midnight. This was considered the period when all signals were operating in the normal mode. The test compared mean accident rates of the normal operation intersections (control group consisting of 99 locations) with mean accident rates for nighttime flashing operation intersections (treatment group consisting of 70 locations). A Wilcoxon rank-sum test was employed to test the statistical significance of accident rates at the 90 percent level of confidence for this daytime comparison.

A similar comparison of accident rates was conducted for a nighttime period established for the hours between 12:00 midnight and 6:00 a.m. This time period was arbitrarily selected because it is "*the period when flashing operation of signals is most commonly used, simply because the lowest traffic volumes occur in this time period.*" The analysis compared the mean accident rate for the treatment and control groups and the mean accident rate for accidents categorized by collision type and collision severity. Collision types included left-turn, rear-end, and angle collisions for two vehicles and run-off-road for single vehicles. The severity of collision was divided into fatal, injury, and property-damage-only categories. Only the worst case of severity was used for each accident; therefore, a fatal accident that also had two injuries was considered a fatal accident. The Wilcoxon rank-sum test was employed to test the statistical significance of accident rates at the 90 percent level of confidence for the nighttime mean accident rates.

The nighttime analysis further evaluated the data for potential trends in several different categories and/or classifications. These classifications included a geometric grouping, an angle of intersection approach grouping, a speed grouping, an interconnection of signals grouping, and a volume ratio grouping, as shown in Table 5-1. In all cases the grouping of intersections by intersection characteristics resulted in smaller sample sizes than those used to determine the mean accident rate for the nighttime period.

Table 5-1. Groupings for Marson's Accident Analysis

Grouping	Division
Geometrics	4-leg, 1 or 2 streets are 1-way. 4-leg, both streets are 2-way and undivided. 4-leg, both streets are 2-way and 1 or 2 are undivided. 3-leg, both streets are 2-way.
Angle of Intersection	More than 70 degrees. 70 degrees or less.
Speed	Greater than 40 mph. 40 mph or less.
Signal Interconnection	Interconnected. Isolated.
Volume Ratio	Less than 2. Between 2 and 4. Greater than 4.

Mean accident rates were used to determine if there were significant differences between operations for intersection type accidents and collision severity. The analysis of intersection geometry, degree of intersection skewness, posted speed of approaches, and degree of isolation provided no clear distinction of higher accident rates for either operation. However, the interconnected intersections in the isolation study did have a significant increase in the rear-end accident rate for normal operations. The analysis of the study sites by intersection ADT ratios revealed a significant increase in the left-turn accidents for flashing operations compared to normal operation. However, the control group had significantly higher rates for property damage, rear-end, and run-off-road classifications. Volume ratio comparisons revealed a statistically significant increase in angle accidents for flashing operation with volume ratios between two and four. However, the control group had significantly higher rear-end and property-damage-only accident rates for volume ratios less than two and greater than four. No trends were established in the statistical correlation of accident frequency and severity to intersection volume.

Marson determined that there was a significant difference in rear-end accidents at locations with regular operation as compared to locations with flashing operation. Marson concluded that his study of flashing signal operation *"...did not define a clear advantage of one signal operation over the other"* (5).

This study attempted to analyze a wide variety of facets associated with intersection accidents. In doing so, several areas of analysis were ambiguously reported in the study. For instance, it was unclear how the varying study periods for the 21 intersections collected from the Macomb County Road Commission were accounted for in the study results and how many of these locations contributed to the intersection categories for the nighttime analysis. Since this study used a comparison of accident characteristics between two samples (i.e. mean accident rate, severity rates and collision type rates), it would be expected that the study period remain consistent within analysis groups. Both the treatment and control sites would have the same study period (in years or months) from which to observe accident frequencies and calculate accident rates. Although it is not stated in the report, the use of accident rates in the comparison assumes that intersections with a shorter study period will experience the same observed accident trend for a longer study duration. However, intersections with a six-month study period might not clearly depict trends for a two-year study period. Although the assumption that accident trends are continuous for intersections with a shorter study period is not entirely inappropriate, there exist instances in the analysis where such an assumption may lead to erroneous conclusions. For instance, in several of the intersection characteristic studies, intersections were grouped into small sample sizes. If intersections with shorter study periods were over-represented in these groups, then conclusions drawn from the statistical comparison could be erroneous. It was not possible to evaluate this issue since the study did not indicate which intersections were used in each group analysis.

Federal Highway Administration Study, 1980

The FHWA study (6), as pointed out earlier in Chapter 2, is the most comprehensive study of flashing traffic signal operation. Within this research, two studies examined separate accident data to determine trends related to flashing and non-flashing signalized intersections. The two studies can be identified as 1) the San Francisco study and 2) the national study. Within these studies, accidents were evaluated for rear-end, right-angle, approach turn, pedestrian/bicycle, and other collision trends. Also, accident severity was evaluated for personal damage only, personal injury, and fatality classifications.

San Francisco Study

A computerized accident file was used to compile accident data between 1974 and 1977 for 520 intersections in the City and County of San Francisco. During this period, San Francisco was in the process of converting a large number of its signals to nighttime flashing operations. Of the 520 intersections: 375 intersections changed operations from normal to yellow/red flash, 36 intersections changed operations from normal to red/red flash, 107 intersections had no operational change, and 2 intersections changed operations from yellow/red flash to red/red flash.

Accidents in the San Francisco area were compiled and split into two groups: 1) those occurring between 6 a.m. and midnight and 2) those occurring between midnight and 6 a.m. Accident rates per year were calculated for intersections grouped by the type of operational change made during the study period. Accident rates were compared for before-and-after periods established by the date of the operational change. To statistically test for a change in accident rates, an expected accident frequency was calculated based on the number of days of exposure in the study period and compared to the observed frequencies. A chi-square test was chosen as the statistical tool for analyzing the rates.

The San Francisco study revealed a significant increase (95 percent significance level) in right-angle accident rates only for intersections where normal operation had been replaced by yellow/red flashing operation. There was also a significant increase in property damage only and personal injury accident rates for the same operational change. There was no significant change in accident rates for the 107 intersections that did not change operation.

A majority of the San Francisco study focused on a second analysis which evaluated a subset of the previously mentioned intersections. This second analysis differed from the first in that it only included intersections that had at least one accident in either the before or after period. The data set consisted of 202 intersections that changed from normal operation to yellow/red flash, 19 intersections that changed from normal operation to red/red flash, 60 intersections that had no operational change, and 2 intersections that had yellow/red flash changed to red/red flash. The study subdivided each operational group (normal, red/red, yellow/red) by intersection location in urban areas, signal system type, and intersection geometry. Intersection location was further divided into central business district, industrial, outlying business district, high density residential, and low density residential. The signal system type was divided into arterial systems and network systems. Intersection geometry was divided into four leg (subdivided into right-angle, offset, and skewed), three leg (right-angle), and more than four legs.

The second analysis, using intersections that had at least one accident in either the before or after period, revealed similar results to those of the first analysis. For locations where normal operations had been replaced with yellow/red flash, the analysis found significant increases in right-angle, property damage only, and personal injury accident rates in at least one subdivision of all classifications (i.e. intersection location, signal system type, and intersection geometry). For the same operational change, right-angle collisions increased in the central business district, industrial district, outlying business district, and high density residential locations. Both arterial and network system intersections had significant increases in right-angle accident rates when yellow/red flashing operations were used. Also, in the geometric classification 90 degree, four-legged intersections showed a significant increase in right-angle collision rates for yellow/red flashing operations. However, accident rates from the second analysis were deemed artificially high by the researchers because they included only sites where accidents had occurred in either the before or after study period.

The methodology employed in the second San Francisco study limits the application of the study's results because it was restricted to intersections that had experienced at least one accident within the defined study period. It was reported in the study that the calculated accident rates were "*...artificially high (by an average of 84 percent)*" because locations where no accidents were observed were excluded from the analysis. Unfortunately, the first San Francisco area analysis did not investigate all of the operational concerns expressed in the second analysis. The first investigation did not include a corresponding analysis of accident rates for intersections grouped by land use, signal system type, and intersection geometry.

National Study

A second group of accidents was collected for 94 intersections throughout the country. The intersections were selected from outside of San Francisco to obtain a variety of geographic, geometric, traffic, and signalization characteristics. The national analysis also used a before-and-after study approach; however, it included intersections that did not observe accidents during the study period.

This analysis used a three-year before and one-year after study period. The selected sample size was reduced to 59 test locations for the study period. Sources for accident data varied from manual record keeping systems to computerized record systems. Accidents at the selected study locations were analyzed by grouping intersections under the same intersection characteristics as the second San Francisco study and then calculating accident rates per million vehicles entering the intersection. A volume ratio test was also used to analyze the study sites. The volume ratio test grouped the data by the ratio of major street volume to minor street volume for the traffic volumes during flashing operation.

The analysis of the 59 intersections revealed similar results as the first two San Francisco studies. Right-angle accident rates were higher for intersections in the outlying business district and high density residential locations and also for four-legged 90-degree intersections. However, the analysis of accident severity revealed a significant increase for only four-legged, 90-degree intersections. The results from the volume ratio analysis indicated significant increases in right-angle accident rates for volume ratios between two and three (major street volume to minor street volume).

The results for the national survey of flashing locations encompassed a multiplicity of cities and states. These locations were chosen to "*...obtain a variety of geographic, geometric, traffic, and signalization characteristics.*" Because the nature of this study was to incorporate diversity into the study site selection, some caution is advised when comparing the results to locally isolated studies. One reason for such discretion is that the report did not clearly indicate if regression-to-the-mean (r-t-m) was considered in selecting the study sites. The r-t-m phenomenon suggests that if a site has an unusually high number of accidents occurring before a treatment, then accident occurrence at the same site the following year would in all probability, be lower, apart from any intervention at that site (41). Generally, locations are submitted for evaluation because accidents at the sites are unusually high. This sampling bias can seriously affect conclusions drawn from expected accident trends.

Portland, Oregon Study

This study (10) investigated flashing operations by analyzing accidents at thirty intersections in Portland, Oregon. The study compared before-and-after accident data of one or two years each for several categories. The categories in which the intersections were classified include:

- **Volume ratios:** zero to twice as much volume on the major-street approach as on the minor-street approach, two to four times the volume on the major, and more than four times greater major-street volume.
- **Street classification:** an arterial intersection with a collector, arterial with a local, collector with a local, collector with a collector, local with a local, arterial with a local or collector.
- **Type of approach:** two-way to two-way, two-way to one-way, one-way to one-way.
- **Speed limit:** posted approach speed less than or equal to 30 miles per hour (mph) and greater than 30 mph.
- **Presence of parking:** parking and no parking.

The before-and-after accident data was collected at thirty intersections where flashing operations had been implemented and then removed within a three-year period. For analysis purposes the accident data was split into accident type and accident severity. Accident rates were calculated for each intersection. These rates represented the average number of accidents per million vehicles passing through the intersection, for each location. The analysis evaluated two accident types (rear-end and angle) and two severity classes (property damage only and injury). A measure of the relative severity of accidents at each location was calculated by a severity index (SI), which is the proportion of total accidents in which an injury or fatality occurs. The SI equation is shown in Equation 5-1. The severity index was used as a supplementary measure of intersection safety. A Student's t-test was used to evaluated statistical significance for comparisons of accident rates and means.

$$SI = \frac{fatal+injury\ accidents}{total\ accidents} \tag{5-1}$$

Results from the study indicated significant increases in angle type collisions and in the injury severity class. A comparison of total intersection accident rates revealed that intersections with volume ratios between 2 and 4 (sample size of 14 intersections) had a significant increase in accident rates during flashing operations. Angle accidents also were found to increase significantly with volume ratios greater than 4 (sample size of 12 intersections). Table 5-2 presents the sample size determined by the volume ratio division.

Table 5-2. Oregon Study Sample Size by Volume Ratio

Volume Ratio	Number of Intersections
< 2	4
2 - 4	14
> 4	12

Grouping intersections by street classification revealed significant increases in accident rates for arterial-to-collector, collector-to-collector, collector-to-local, and local-to-local intersections. Intersections of local streets to local streets experienced the greatest increase in accident severity. Table 5-3 presents the sample size determined by the intersecting street type division.

Arranging the intersections by their type of approach revealed that two-way to two-way intersections had significantly higher rear-end and angle accidents for flashing operations. With the division of intersections by posted speed, a significant increase in angle accidents was observed, regardless of the posted speed. The analysis of parking conditions lacked reliable information and was deemed inconclusive.

The small intersection groupings in this study delineate one of the more common problems associated with intersection accident analysis. It is a very arduous task to find sufficiently large sample sizes that will adequately reflect changes in accident trends due to imposed treatments.

Table 5-3. Oregon Study Sample Size by Intersecting Street Type

Street Classification	Number of Intersections
Arterial/Collector	2
Arterial/Local	4
Collector/Local	11
Collector/Collector	6
Local/Local	7

In several instances in this study, comparisons were made on less than desirable sample sizes. Generally, using accident rates alleviates some of the concerns arising from evaluating small samples because rates can provide a normalized ratio as a basis for comparison. However, arithmetically averaging small sets of ratios might render a misrepresentation of actual accident trends.

Accident Analysis Methodology

Much of the information gleaned from the preceding studies was used to aid in establishing the design of this investigation. The study design focused on concerns in previous research that had revealed discernable accident trends.

Study Site Location

The accident investigation required locating a sufficient number of signalized intersections to support a valid statistical analysis. Chapter 3 described a survey administered to traffic engineers throughout the state. From the survey, TxDOT districts and local agencies indicated whether their area used flashing operation. Appropriate districts and agencies were contacted for a listing of intersections that flash. Each district and agency was requested to supply pertinent information on each intersection that currently flashes or had flashed within the last ten years. Other pertinent information requested included: the date of flash implementation or flash removal, time of day for flashing operation, and day(s) of week that the signal operates in the flashing mode. From the responses, potential study sites were identified for a representation of both urban and rural localities.

Study site selection was limited to four-leg, bi-directional signalized intersections. To exclude as much uncertainty as possible, a near perfect geometric configuration was sought. Desirably, each approach of the candidate intersections was to be approximately perpendicular with adjacent approaches. The literature review and traffic engineer survey indicated that motorist confusion may be associated with some flashing signalized intersections. This confusion arises when motorists are unsure of cross street control, whether they have legal right-of-way or are required to stop. It is conceivable that motorist confusion can be compounded by flashing signals and unique geometric configurations. In an effort to focus specifically on accidents related to the flashing signal operation, the study focused on four-legged intersections. No one-way systems were evaluated. For the reasons just cited, only two-way, bi-directional intersections were analyzed.

The potential study site locations were evaluated using the criteria outlined above. Initially, over 200 intersections were identified as meeting the selection requirements. The data set was divided into three primary groups: 1) continuous flashing operation, 2) locations that had an operational change, and 3) 24-hour normal operation. The continuous flashing operation group contained signals that flashed continuously throughout the study period. The before-and-after group contained signals that were changed from normal operation to flashing operation or vice versa sometime during the study period.

Accident Records

The actual accident records are vital to the study of accidents related to flashing signal operation. An accident form is filed by the investigating officer from the local or state police enforcement agency. The original copy of the accident report is maintained at the local level and a copy is sent to the Texas Department of Public Safety (DPS). The DPS maintains all accident records for the State of Texas.

The accident forms supply valuable information about each accident such as: date, time, place of accident, and whether alcohol or weather conditions were a factor. Therefore, access to this information was important to the study. The actual accident form is available for a fee (approximately \$3 per copy); however, this avenue would have exhausted the study budget (over 3,500 observations were identified, as discussed later). Therefore, an electronic file format was located.

The DPS maintains an electronic file on all accidents occurring on state maintained roads and on roads in participating cities. A participating city provides copies of accident reports on city roads to the DPS. For each accident record that is filed with the DPS, the information has to be input into a master accident file. In order to identify accident locations in a consistent format, each accident that occurred on a state road is assigned to a specific location identified by Control-Section-Milepoint. For accidents that occur on local streets, the location is identified by the first five letters of the primary and secondary road name. The relevant information concerning the accident is coded into the accident file. The DPS releases this information to TxDOT for research and other purposes.

Although the electronic file provides much valuable information, actual accident records were obtained for verification to the master accident file. Several local agencies supplied copies of their reports for specific intersections.

Rural Versus Urban Locations

The accident data was grouped by the population of the metropolitan area. Intersections were classified as urban for populations greater than or equal to 50,000 and as rural for populations less than 50,000. The break point of 50,000 was chosen for two primary reasons: first, the 1990 Green Book (16) uses 50,000 as a distinction between small urban areas and large urban areas, and second, the State of Texas master accident file presently had a break point at the 50,000 population.

Study Period

Accidents are random events, meaning that it is nearly impossible to predict just when, where, or how an accident may occur. Therefore, it is necessary to collect and analyze accident data over an extended period to correctly identify a valid trend. For the accident study, accident records from January of 1985 through December of 1992 were collected and analyzed. Although accidents were collected for eight years at each location, only four consecutive years of data were used at any one location for comparison needs. Intersections that had a change in signal operation, either from normal to flashing operation or vice versa, had a four-year study period within the total eight-year study time span. The four-year time period was established by the implementation date of the operational change. Therefore, if an intersection had an flashing operation implementation date in May of 1987, then its corresponding study period would be from May of 1985 to May of 1989. The implementation date also defines the before-and-after periods for study, so for the same example the before period would be from May of 1985 to May of 1987 and the after period would be from May of 1987 to May of 1989. The identical time periods were applied to control sites for comparisons.

Accident Frequency Versus Accident Rate

Accident frequency is the number of accidents that occur at a designated place during some specified time period. Accident frequency can reflect the number of accidents that occur during an hour, a day, a month, a year, etc. Accident rate is the accident frequency divided by the traffic volume. Both the accident frequency and traffic volume must be representative of the same location and time. The advantage of using the accident rate method of evaluating a given signal operation (or anything else) is that locations with high traffic volumes are normalized for comparison with lower traffic volume locations. The disadvantage of using accident rates is the requirement of obtaining a representative traffic volume for each study site. For an intersection analysis, traffic volumes would be required on all four approached in order to determine the total number of vehicles entering into the intersection. These volumes provide the most consistent description of vehicle exposure to conflicting movements. Due to the limited availability of traffic volume data, this accident analysis used frequency as the basis of comparison between the various types of signal operation.

Study Site Selection

From the eight-year study period, 171 intersections were identified for analysis. Each intersection's flashing operation date was used to place it in one of the four groups shown in Table 5-4. Figure 5-1 illustrates the percentage and number of intersections that were collected for each group.

Table 5-4. Description of Intersection Control Groups

Control Group	Description	Before Condition	After Condition	Abbreviation
1a	Locations where flashing operation was implemented between 1986 and 1991.	Normal	Flash	Normal/Flash
1b	Locations where flashing operation was removed between 1986 and 1991.	Flash	Normal	Flash/Normal
2	Locations that operate on 24-hour normal (full-color) operation between 1986 and 1991.	Normal	Normal	Normal/Normal
3	Locations where flashing operation was implemented prior to 1986.	Flash	Flash	Flash/Flash

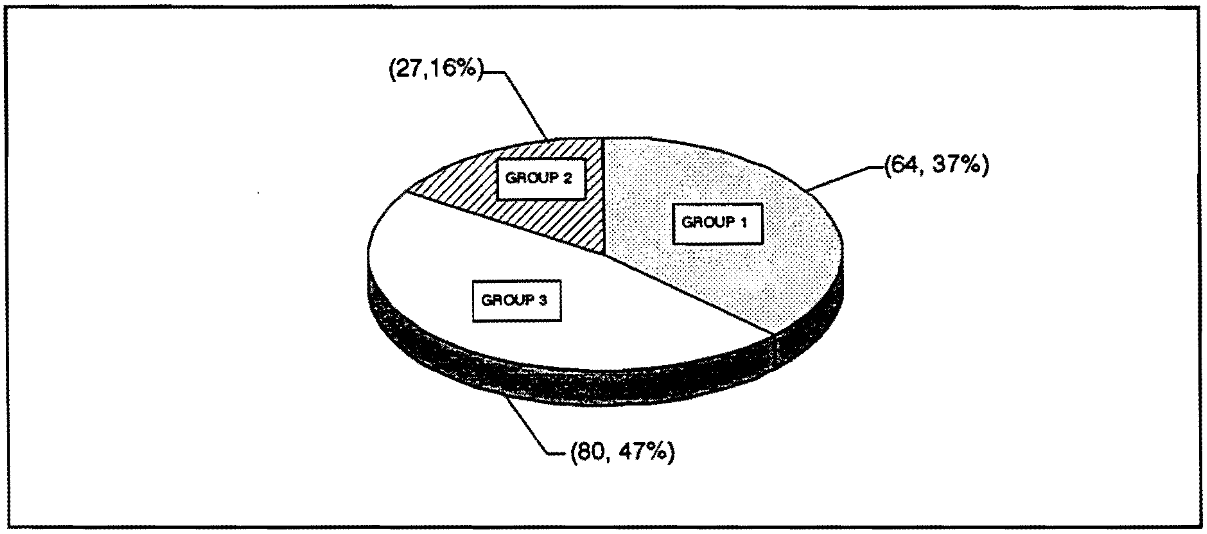


Figure 5-1. Group Sizes by Number and Percentage

Daytime Comparisons

Prior to investigating accident trends for intersection groupings, a test of whether or not these groups came from the same population was conducted. Daylight hours of operation were selected as the time period to compare the groups because all intersections operated in the normal mode at this time. Daytime accident frequencies were collected for all of the intersections for the years 1988 and 1989. The hours of normal operation between 8:00 am and 4:00 pm were chosen to represent daytime hours of operation. A scatter plot was created to determine if there was an underlying trend in accident frequency distributions.

Scatter Plot

A scatter plot is a rudimentary statistical tool that can provide quick insight on trends between two variables. Generally, trends can be seen as clusters of data points. A regression of the data points can be conducted to determine if the clusters have any significant meaning.

Rural and Urban Scatter Plot

The intersections were first divided into two classes - urban and rural. Daytime accidents for two consecutive years were recorded for each intersection. The distinction between urban and rural locations was created because it was expected that the rural locations would generally have intersections with a low number of accidents and that urban locations would mostly have intersections with a high accident frequency. That is, rural locations were expected to have less than two accidents per year with a high probability of having no reported accidents at all, and urban intersections were expected to have the opposite propensity. However, the scatter plot produced no clear distinction between the two classifications. A histogram of the scatter-plot data is shown in Figure 5-2. The vertical axis represents the cumulative number of locations and the horizontal axis represents the number of accidents. The histogram shows that urban and rural locations had a similar number of locations with a high accident frequency and a similar number of intersections with a low accident frequency. It can be seen in Figure 5-2 that there were 94 locations with no reported accidents during the two-year daytime study period.

Intersections were further divided into geometric groups based on the number of through lanes at each intersection approach. Since traffic volume data was unavailable, intersection geometry served as a surrogate measure for grouping intersections. Intersections were divided into three groups, as shown in Table 5-5.

There were some intersections that could have fit into two groups such as a 4×2 or a 6×4. For these cases, the intersections were grouped by the largest size approach, so a 4×2 would be placed in Group B and a 6×2 would be placed in Group C.

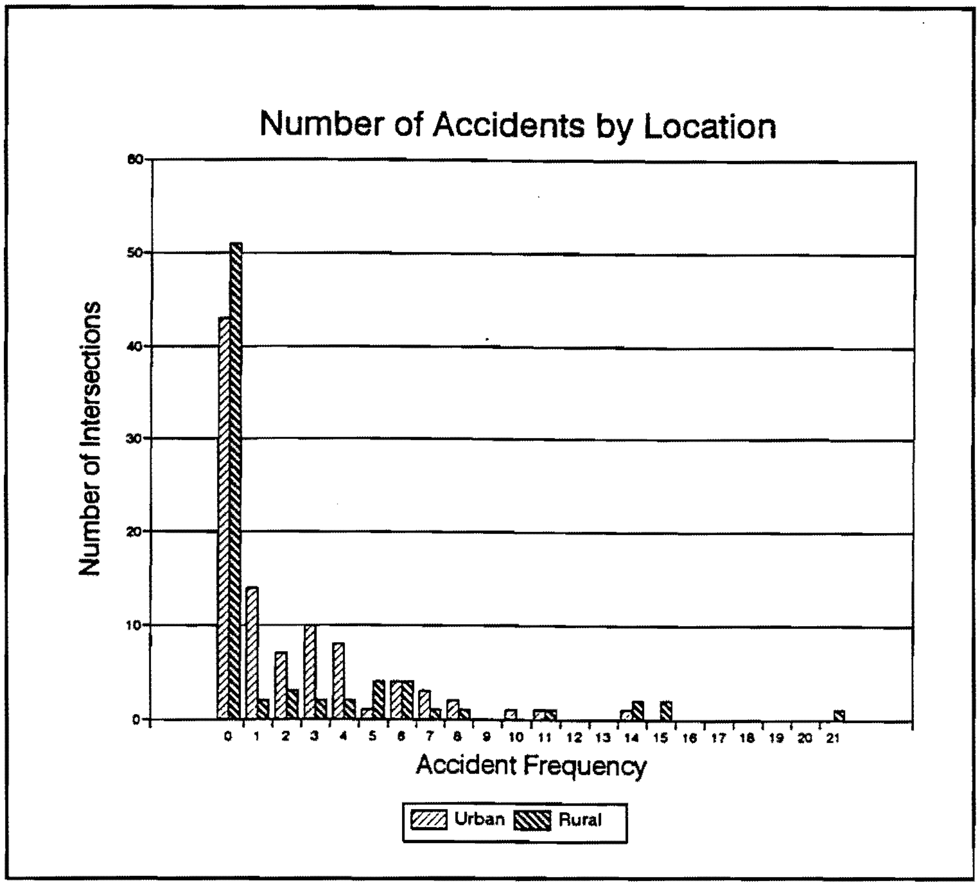


Figure 5-2. Histogram of Accident Frequency by Classification

Table 5-5. Description of Intersection Geometry Groups

Group	Description	Examples[1]
A	Intersections 2 lanes by 2 lanes (2×2).	2×2
B	Intersections larger than 2×2, but smaller than 6×6.	3×2, 4×2, 4×4, 5×2, 5×4, 5×5
C	Intersections 6×6 and larger.	6×6

Note: [1]An odd number of lanes indicates the presence of a left turn lane.

Geometric Scatter Plot

A geometric scatter plot was created using the definitions for geometric Groups A, B, and C. The plot revealed an increasing trend in the number of accidents for increasing geometric size. This meant that larger intersections were more likely to have a higher number of accidents. However, a regression analysis provided a low correlation factor indicating that the trend might not be significant.

As previously mentioned, the daytime analysis revealed that 55 percent of the locations investigated (51 rural locations and 43 urban locations) had no reported accidents during the two-year daytime study period. These locations were noted for the nighttime analysis to determine if a similar accident profile might exist during nighttime operation. A Chi-Square evaluation was used to test the significance of the daytime accident trends revealed by the scatter-plots.

Chi-Square Test of Homogeneity

The Chi-Square test served two main objectives in analyzing daytime accident trends. First, it was used to test for significant differences in accident data between rural and urban locations. Second, it was used to test the significance of accident trends for locations divided by the type of intersection control. In effect the second analysis sought to determine if differences existed that would influence nighttime operational comparisons.

Study sites were tabulated by the type of geometry within urban and rural classifications. Tables 5-6 and 5-7 give the total number of locations for each category. These locations were selected from a study interval from 1987 to 1990, to ensure two years of before and after data. As previously mentioned, the focus of the daylight test of homogeneity is to determine if any of the three intersection groups (identified by type of signal operation) exhibit significant differences in accident trends when using the same type of operation. It should be noted that in the second Chi-Square daytime analysis, no distinction was made between intersections that had normal operations replaced with flashing operation and locations that had flashing operation replaced with normal operations. This distinction was not made in the daytime analysis because all groups operated in the normal mode during the daylight hours. The labeling of intersections with operational changes is provided in the daytime analysis simply to indicate that these are the locations that had an operational change during the nighttime analysis.

Group 1 intersections consist of locations where flashing operation was either implemented or removed. These intersections are later distinguished in separate categories for an analysis of accidents occurring during nighttime hours. Although it is not presented in Table 5-7, intersections that use 24-hour normal operation in the rural area were collected, but later eliminated by geometric study constraints. It was perceived that Group 3 intersections could be used as an alternative comparison group, for which a pertinent discussion is provided in the next chapter.

Table 5-6. Number of Urban Intersections for Daytime Accident Analysis

Intersection Groups	Description of Control	Intersection Geometry Groups			Total
		A (2×2)	B (>2×2, <6×6)	C (≥6×6)	
1	Normal/Flash or Flash/Normal	5	29	22	56
2	Normal/Normal	4	11	12	27
3	Flash/Flash	3	4	6	13
Urban Total		12	44	40	96

Table 5-7. Number of Rural Intersections for Daytime Accident Analysis

Intersection Groups	Description of Control	Intersection Geometry Groups			Total
		A (2×2)	B (>2×2, <6×6)	C (≥6×6)	
1	Normal/Flash or Flash/Normal	--	7	--	7
2	Normal/Normal	--	--	--	--
3	Flash/Flash	23	43	2	68
Rural Total		23	50	2	75
Total - Urban and Rural		35	94	42	171

A two year accident frequency at each location was used to evaluate the distribution of intersections for certain categories. A Chi-Square test was used to determine if significant differences existed for distribution comparisons. Comparisons were tested at the 95 percent confidence level with a correlating alpha value of 0.05. The Chi-Square tables were collapsed until no cell had less than one observation and no more than 20 percent of the cells had less than five observations.

The first Chi-Square test evaluated homogeneity between rural and urban distributions based on the frequency of accidents at each intersection. This test was conducted to determine if rural and urban locations should be separated in any further analysis. It was expected that urban locations would have more locations with a high two year accident frequency when compared to rural locations. Table 5-8 shows the Chi-Square table used to test the homogeneity of urban and rural locations. Values in the individual cells represent the number of intersections with the number of accidents shown in the corresponding column. As shown in the table, there are 44 urban and 50 rural locations that had no reported daytime accidents. A computed Chi-Square value of 14.46 revealed a significant difference (at the 95 percent confidence level) when compared to a table Chi-Square value of 11.07 for five degrees of freedom. Since rural and urban locations were shown to be significantly different, the remaining tests evaluated rural and urban distributions separately.

Table 5-8. Daytime Homogeneity Test 1: Accident Frequency Distribution for Rural and Urban Intersections

Intersection Category		Intersection Accident Frequency						
		0	1	2	3-5	6-7	>7	Total
Urban	Observed	44	15	7	19	6	5	96
	Expected	52.7	9.5	5.6	15.1	6.1	6.7	
Rural	Observed	50	2	3	8	5	7	75
	Expected	41.2	7.4	4.3	11.8	4.8	5.2	
Observed Total		94	17	10	27	11	12	171

The next comparison evaluated the distribution based on the type of operational change made during the nighttime period. This comparison used daytime accident frequencies to determine if locations that had nighttime operational changes can be compared to locations that had no nighttime operational change. Again, it should be understood that all intersections operated in the normal mode during the daytime analysis. In these Chi-Square tests, Group 1 represents locations where an operational change had been implemented during the nighttime study period. Thus, the Chi-Square tests are comparing locations that had no operational change to those that had an operational change to determine if there are significant differences in the daytime accident frequency distribution for each location. These comparisons were conducted during the daytime period of operation when all intersections operated in the normal (red-yellow-green) mode. Therefore, all accidents used in these comparisons occurred when the intersections were in normal operation.

Tables 5-9 and 5-10 are sample comparisons of accident distributions made for separated rural and urban locations. The comparisons evaluated pairs of intersection groups using two distribution categories - locations with and locations without accidents. These tests were conducted to show that intersections were pooled from the same population for paired intersection groups depicted by the type of signal operation. The pairs that are used in the Chi-Square comparisons were determined by the type of nighttime operational change. Although it is not shown, the accident distribution for urban group 3 (Flash/Flash) was compared with the urban group 1 (Flash/Normal or Normal/Flash). In each case, no significant difference (95 percent confidence level) was found between pairs of comparison groups.

Table 5-9. Daytime Homogeneity Test 2a:
Rural Intersections Categorized by Accident Frequency Distribution

Intersection Location			**Intersection Accident Frequency**		
			0	**>0**	**Total**
Rural	1 - Normal/Flash or Flash/Normal	**Observed**	6	1	7
		Expected	4.3	2.6	
	2 - Flash/Flash	**Observed**	34	24	58
		Expected	35.6	22.3	
Observed Total			40	25	65

Table 5-10. Daytime Homogeneity Test 2b:
Urban Intersections Categorized by Accident Frequency Distribution

Intersection Location			**Intersection Accident Frequency**		
			0	**>0**	**Total**
Urban	1 - Normal/Flash or Flash/Normal	**Observed**	23	33	56
		Expected	23.5	32.4	
	2 - Normal/Normal	**Observed**	6	7	13
		Expected	5.4	7.5	
Observed Total			29	40	69

Accident distributions were also evaluated for geometric groupings. Intersections were divided by rural and urban locations and then placed into separate geometric groups as previously shown in Tables 5-6 and 5-7. It was expected that larger geometries might have a higher accident frequency than smaller intersections. In both the rural and urban comparisons the Chi-Square test revealed no significant difference (95 percent confidence level) in the accident distribution created by the geometric categories. The 94 locations (51 rural locations and 43 urban locations) that had no reported accidents were noted for the nighttime analysis to determine if a similar accident profile might exist during nighttime operation.

Summary of Daytime Accident Investigation

There were two main purposes for the daytime accident investigation. The first goal was to establish that all of the intersections were pooled from the same population of intersections. The Chi-Square test of accident frequencies was used to determine if variability existed between the collected intersections. The Chi-Square test revealed a significant difference between rural and urban intersections. This indicates that rural and urban locations cannot be combined for the nighttime analysis. In addition, comparisons were conducted for paired groups based on the type of nighttime operational change. The paired groups were selected from groups that might be compared in the nighttime accident investigation. The Chi-Square test revealed no significant differences for accident distributions of the paired groups. The second goal was to delineate possible accident trends that could be evaluated in the nighttime investigation. It was hypothesized that intersection characteristics, such as 2X2 or 4X4 geometry, might exhibit distinctive accident distributions. No statistically significant geometric trends were found in the Chi-Square comparisons or scatter plots. It was noted, however, that there were a large number of locations that had no daytime accidents. These locations were noted and later used to determine if a zero accident profile remained during the nighttime evaluation.

Nighttime Analysis

There are two basic statistical approaches to analyzing accident frequencies: a before-and-after study, and a comparative analysis study. These tests evaluate a measure-of-effectiveness (MOE) that is associated with a treatment implemented on a study group. The MOE used in this study is the frequency and severity of accidents, and the treatment is the use of flashing operations during nighttime periods. The nighttime evaluation used the before-and-after with control study design.

Before-and-After Study with Control

The before-and-after study uses the same site(s) to evaluate the effects of a treatment (41). Observations are made for a fixed period of time before the treatment is implemented and then continued for the same period of time after the treatment. A control group that is characteristically similar to the study group is also observed over the same period of time. This type of study reduces external variables from affecting the areas of interest by restricting variability to the study group. Observations are made on the same site before and after the treatment, and inferences can be drawn on the treatment's effects. Figure 5-3 displays a typical before-and-after study design. In the figure, the shaded bar represents the period in time when the treatment is implemented at the study site(s). The point in time of the implementation defines the before and after study periods for evaluation of the MOE. The comparison group serves as a measure for variables that are common to both groups (and influence results) but are not variables related to the treatment. This test assumes that both the study sites and controls sites will experience the same accident exposure. The Odds Ratio test was selected as the statistical tool to evaluate the accident MOEs.

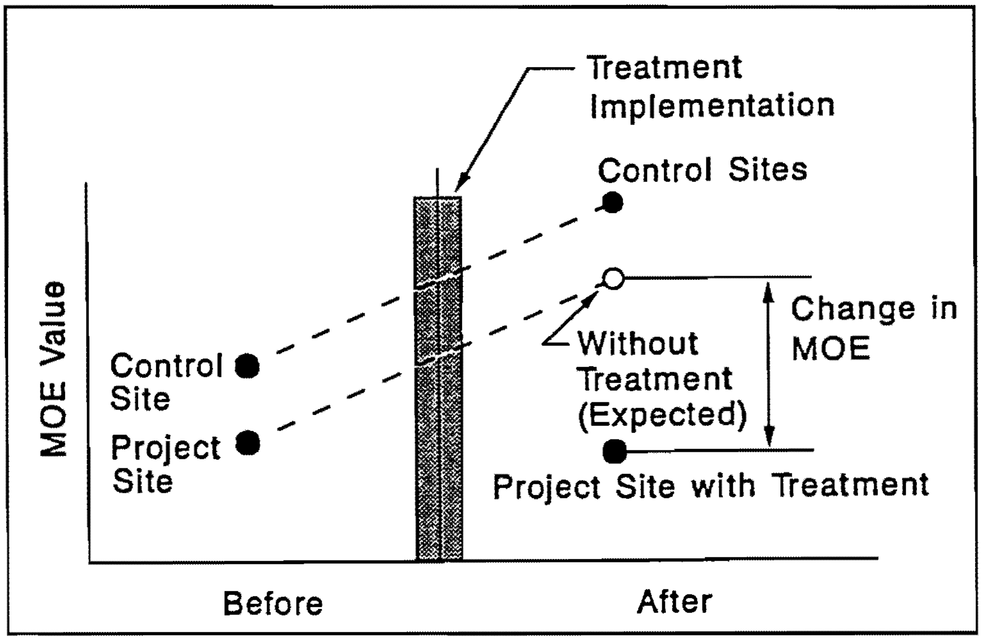


Figure 5-3. Typical Before-and-After Study Design

Odds Ratio

Accident frequencies during the nighttime period were analyzed for a two-year before and a two-year after study period established by the date of change in signal operation for Group 1 intersections. An Odds Ratio test of significance (42) was used to test changes in accident frequencies. An Odds Ratio (frequency cross product ratio) estimate was conducted on the intersection groups. This test relies on accident frequencies to determine changes in accident

MOEs. The test statistic has a standard normal distribution and is compared to normal z-values at a specified level of significance. The following example demonstrates how the Odds Ratio is calculated. Observations are first placed in the two-by-two matrix form shown in Table 5-11.

Table 5-11. Sample Odds Ratio Table

Time Period	Comparison	Treatment
Before	A	B
After	C	D

Values are computed to determine the effectiveness of the treatment by calculating a ratio of the accident frequencies.

The Odds Ratio estimate of treatment effectiveness is:

$$Odds\ Ratio = \left[\frac{A/C}{B/D}\right] \tag{5-2}$$

The statistical test of significance for this estimate is:

$$T = \left[\frac{Ln(Odds\ Ratio)}{S.D.(Odds\ Ratio)}\right] \tag{5-3}$$

Where S.D. represents the standard deviation of the Odds Ratio, as follows:

$$S.D.\ (Odds\ Ratio) = \sqrt{\frac{1}{A}+\frac{1}{B}+\frac{1}{C}+\frac{1}{D}} \tag{5-4}$$

The estimate is interpreted as a percent reduction by computing an 'x' variable, as follows:

$$x = (Odds\ Ratio - 1) * 100 \tag{5-5}$$

The treatment has a significant increase (if x is positive) or decrease (if x is negative) in accidents by x percent if the absolute value of T exceeds 1.96 (for a 5-percent level of significance). Otherwise, the treatment has caused no change. Using a 95-percent confidence level (i.e. the 5-percent level of significance) the findings are determined in the following manner:

if $|T| > 1.96$ and $x > 0$, then the treatment has a significant increase,
if $|T| > 1.96$ and $x < 0$, then the treatment has a significant decrease,
if $|T| \leq 1.96$, then the treatment has caused no change.

The Odds Ratio test was used to determine significant changes in accident data when flashing operation was implemented. The same intersections that were used in the daytime analysis were candidate locations for the nighttime analysis.

The sample sizes of the intersections for the nighttime analysis is smaller than those for daytime analysis because some intersections were eliminated by the two-year study period constraint. Because the focus of the nighttime analysis was to determine if flashing operation influences intersection safety, a distinction had to be made between locations where flashing operation was implemented and locations where flashing operation was removed. This distinction was not needed for the daytime analysis because all of the locations used normal operation during daylight hours. The resulting size of the intersection groups for the nighttime analysis are provided in Tables 5-12 and 5-13.

Table 5-12. Number of Urban Intersections for Nighttime Accident Analysis

Intersection Control Groups	Description of Control	Intersection Geometry Groups			Total
		A (2×2)	B (>2×2, <6×6)	C (≥6×6)	
1a	Normal/Flash	4	21	16	41
1b	Flash/Normal	0	4*	3*	7*
2	Normal/Normal	4	11	12	27
3	Flash/Flash	2	4	6	12
Urban Total		10	40	37	87

Note: *These locations were all obtained from one urban environment.

As is obvious in Table 5-13, there are several cells that do not have locations. This is due to a number of intersections that were identified for these cells but later eliminated due to geometric and time constraints. Most notable is the absence of 24-hour normal operation control sites, locations that had normal operations replaced with flashing operations, and the larger size (Group C) intersections. It was generally found in the rural category that most of the intersections collected had flashing operations implemented prior to the study period. Of those rural intersections that did have an operational change between 1985 and 1992, only locations that had flashing operation replaced by normal operation matched the study constraints.

Table 5-13. Number of Rural Intersections for Nighttime Accident Analysis

Intersection Control Groups	Description of Control	Intersection Geometry Groups			Total
		A (2×2)	B (>2×2, <6×6)	C (≥6×6)	
1a	Normal/Flash	--	--	--	--
1b	Flash/Normal	1	7	--	8
2	Normal/Normal	--	--	--	--
3	Flash/Flash	23	43	2	68
Rural Total		24	50	2	76
Total - Urban and Rural		35	94	42	163

Note: *These locations were all obtained from one urban environment.

Two types of comparisons were developed to separately analyze intersections that had an operational change. Intersections that had normal operation replaced with flashing operation (Group 1a) were compared to locations that had normal operation throughout the before-and-after periods (Group 2). Intersections that had flashing operation replaced with normal operation (Group 1b) were compared to locations that had flash operation throughout the before-and-after periods (Group 3). It was perceived that this evaluation would basically invert the type of treatment evaluated by reversing the comparison. In other words, instead of the treatment being the implementation of flashing operations, it would be the implementation of normal operation at the study sites. Therefore, two comparisons were conducted to determine the impact that flashing operations have on accidents. One comparison evaluated the impacts of implementing flashing operation, and the other evaluated the impacts of removing flashing operation. The ability to conduct both of the comparisons was restricted by the availability of intersections for comparison. Therefore, the rural analysis was limited to a comparison of locations that had flashing operation replaced with normal operation. Figure 5-4 provides a graphical representation of the comparisons conducted.

In the first comparison, intersections that had flashing operations implemented (Group 1a) are compared to intersections with 24-hour normal operation. The second comparison examines intersections that had flashing operations removed (Group 1b) compared to locations where

Evaluation of Implementing Flashing Operation

Comparison Groups		Before Condition (2 years)	After Condition (2 years)
Group 1a	Treatment	Normal Operation	Flashing Operation
Group 3	Control	Normal Operation	Normal Operation

Evaluation of Removing Flashing Operation

Comparison Groups		Before Condition (2 years)	After Condition (2 years)
Group 1b	Treatment	Flashing Operation	Normal Operation
Group 2	Control	Flashing Operation	Flashing Operation

Figure 5-4. Before-and-After Comparisons

flashing operations have operated consistently throughout the 1985-1992 study period. As was previously mentioned, the difference in the two comparisons is that the first comparison uses normal operation as a control for comparison, and the second comparison uses flashing operation as a control for comparison. Theoretically, there is no difference in which manner the locations are compared as long as the appropriate time periods are used in the control locations.

Accident data were collected for the nighttime period from midnight to 6:00 am. Analysis of the accident frequencies for the nighttime period used the same type of geometric group classification (i.e. Group A, Group B, and Group C) as the daytime analysis. The 94 locations that did not have accidents during the daytime analysis were further evaluated to determine if nighttime operations revealed a change in the zero accident profile.

Results of Accident Analysis

As previously mentioned, the study sites were separated into rural and urban categories for analysis. A total of 85 accidents were reported for the entire nighttime study period consisting of two years of before data and two years of after data. Accident analysis results showed that the rural category did not provide any observations during the nighttime period; therefore, a statistical analysis of the intersection accident frequencies and collision severity was not possible. Hence, the following discussion of the Odds Ratio analysis focuses on those intersections in the urban category. Urban accident data were collected for Intersection Control Groups 1a, 1b, 2, and 3. Table 5-14 shows the total number of accidents collected for each group.

Table 5-14. Urban Area Nighttime Accident Frequencies

Time Period	Number of Accidents for Each Intersection Control Group			
	Group 1a Normal/Flash	Group 1b Flash/Normal	Group 2 Normal/Normal	Group 3 Flash/Flash
Before (2 years)	13	1	12	2
After (2 years)	32	0	13	12
Total Accidents	45	1	25	14

Table 5-15 provides the accident frequency for collision type and collision severity at intersections where flashing operation was implemented. A table was not produced for those intersections where flashing operation was removed because there was only one observation. For each before-and-after cell in Table 5-15, an Odds Ratio value was computed using the aforementioned comparison to accident frequencies at intersections with normal operation. All tests were conducted at the 95 percent confidence level.

Table 5-15. Urban Nighttime Accident Frequencies for Intersections where Flashing was Implemented

Accident Categories		Intersection Geometry Groups					
		Group A 2×2		Group B (>2×2, <6×6)		Group C (≥6×6)	
		Before	After	Before	After	Before	After
Type of Collision	Rear-end	0	0	0	0	2	0
	Angle	1	0	7	27	0	3
	Other	0	0	0	2	3	0
Accident Severity	Incapacitating Injury	0	0	0	3	1	0
	Non-incapacitating Injury	0	0	3	6	3	0
	Possible Injury	1	0	4	9	0	2
	Fatality	0	0	0	1	0	0
	Property Damage Only	0	0	0	10	1	1
Total Number of Accidents		1	0	7	29	5	3

In several cases the Odds Ratio test statistic could not be directly calculated because of a zero frequency in several cells. Since the test statistic in the Odds Ratio calculations uses a logarithmic function, it is not possible to account for a zero ratio. However, in these instances each cell in the Odds Ratio table may be increased by one to calculate the test statistic. Since the test is a ratio of frequencies, the increase serves only to circumvent the problem with calculating the natural log of zero, and does not influence statistical significance.

An examination of the aggregate accident frequencies for both types of comparisons did not reveal any statistically significant changes in accident observations. Results from the two comparisons are shown in Table 5-16. Therefore, additional evaluations were conducted to determine if there were any accident trends as a function of geometric size, type of collision, or accident severity.

Table 5-16. Results of Nighttime Accident Analysis

Statistical Test	Flashing Operation Implemented		Flashing Operation Removed	
	Treatment	Control	Treatment	Control
	Group 1a Normal/Flash	Group 2 Normal/Normal	Group 1b Flash/Normal	Group 3 Flash/Flash
Before Frequency	13	12	2	1
After Frequency	32	13	12	0
Odds Ratio	2.27		1.38	
Test Statistic	1.58		1.56	
z Statistic (95% confidence level)	1.96		1.96	
Percent Change	none		none	
Finding	No statistically significant increase in accidents due to implementing flashing operation.		No statistically significant decrease in accidents due to removing flashing operation.	

For the intersection geometry analysis, the intersections were divided into the same geometric groups that were used for the daytime analysis. Group B locations, which are mostly 4×4 intersections, had a sizable increase in accidents from 7 to 29 after flashing operations were implemented. However, the geometry analysis did not indicate any statistically significant changes in accident frequency for flashing operations.

The type of collision was also evaluated to determine if there was a statistically significant trend in the type of vehicle collisions for the nighttime period. Two-vehicle collisions were evaluated for the following categories: angle, rear-end, and "other". The Odds Ratio test was used to determine if there were significant changes in the type of collisions between the before-and-after study periods. The number of right-angle collisions did increase with flashing operation but the increase was not statistically significant. Odds ratio test results show that none of the collision categories has statistically significant change in accidents.

An analysis of accident severity was also conducted for the urban intersections. This test divided nighttime accidents into five groups: property damage only, possible injury, incapacitating injury, incapacitating injury, and fatality. Again, the Odds Ratio test was used in intersection comparisons to evaluate significant changes. The results of comparing intersections where flashing operation was implemented to intersections with only normal operation showed an increase in the number of possible-injury, and property-damage-only accidents for flashing operations. However, none of the collision severity categories showed statistically significant changes in accident frequency.

Evaluation of Intersections with Zero Daytime Accidents

An evaluation of the locations that had no reported accidents during the daytime analysis was conducted for the nighttime period. Of the 94 locations that reported no daytime accidents, 30 intersections (23 urban and 7 rural) were locations where flashing operations had been implemented during the study period between 1985 and 1992. In addition 43 of the 94 locations were intersections where flashing operations were implemented prior to 1985. Neither group of intersections deviated from the zero reported accident profile within the four-year before-and-after study duration. At these locations where there were zero reported daytime accidents, the implementation of flashing operations did not affect intersection safety.

Summary of Accident Analysis

The statistical analysis of nighttime accidents did not provide a clear advantage or disadvantage for operating signalized intersections in the flashing mode during nighttime hours with respect to accidents. This is due in part to the large percentage of intersections that did not have an accident during the four-year study period. Approximately 56 percent of the intersections never observed an accident. The complete absence of rural nighttime accidents impeded any further collision or collision-severity evaluation for those locations. This occurred despite the focus of considerable effort on collecting an appropriate and large enough sample size for evaluation. Furthermore, it was perceived that increasing the sample size would not improve statistical results. This is because a larger sample size using the same data collection methods would still have the same percentage of intersections reporting no accidents. However, in the urban analysis certain results correlated with previous research findings. The increase in angle accidents and in the severity of accidents for flashing operations coincides with similar results in preceding studies. The two measures have shown statistically significant increases in all of the previous studies investigated.

One of the largest concerns with the accident analysis was the dependency on a random event for observations. This posed many problems for this study and is the source for many of the inconclusive results of previous studies. Accident analysis is not easily addressed by conventional statistical methods. Some of the confounding problems that impede accurate study results arise from the large sample of locations necessary to conduct accurate testing. For instance, in previous studies, there were usually an insufficient number of study sites to allow for categorization analysis. That is to say, as an aggregate analysis, 30 intersections may be acceptable. But when the 30 intersections are separated into several categories, the resulting smaller sample sizes can limit the clarity of the results. This problem is difficult to avoid and in many of the previous studies, it was not addressed.

Furthermore, a fundamental problem lies in trying to use random events, such as accidents, to establish stable comparisons over short periods of time. The previous studies all used a study period under four years. This short time period problem is augmented when studies of flashing operations consider shorter periods of time in the day which further diminish the chance of observing an accident. It is clearly shown from the lack of observations at the rural intersections that an accident analysis has its limitations in discerning trends over short periods of time.

In addition to the preceding, it was found that collecting a homogeneous sample of sites on a large scale was just not feasible in this study. Many of the locations did not have recent intersection volume data, and many other locations lacked nighttime volume data. Thus, an accurate and reliable calculation of accident rates was not possible with the available volume information.

Despite the limited accident related findings of this study, inferences from the results of previous studies described at the beginning of this chapter can be used to evaluate the safety effects of flashing operations. Similar to the findings of this study, the Portland (10), FHWA (6), Washington, D.C. (3), and Marson's thesis (5) studies showed that flashing operations accounted for statistically significant increases in angle accidents. These studies also indicated an increase in accident severity, with angle accidents contributing to more injury accidents. Although it was not possible to address in this study, the FHWA, Portland, and Marson's studies addressed volume ratios as a measure for correlating intersection safety with flashing operations. In these studies it was reported that volume ratios between two and four revealed significant increases in intersection accidents. In all four of the previous studies, angle accidents contributed heavily to the increase in total accidents. The FHWA report examined the total volume entering the intersection for several ratio classes and concluded that accidents increased when the main street two-way volume was greater than 200 vph during flashing operations.

The findings of this study and a study of flashing operation in Los Angeles County (4) indicate that daytime accident frequency can be used to evaluate the safety impacts of implementing flashing operation. The L.A. study stated that "... *locations with low accident experience during the flashing operation will not have increased accident experience during the same time period if the signals are placed on 24-hour operation*" (4). The accident analysis described in this chapter found that intersections which had zero accidents in the two-year period after flashing operation was implemented also had zero daytime accidents during the two-year period prior to the implementation of flashing operation. This finding can be useful in determining the feasibility of implementing flashing operation. It appears that flashing operation can be safely implemented if the intersection has experienced no accidents during the previous two year period. However, because accidents are random events, the presence of one accident does not indicate a trend or unsafe condition. Therefore, the presence of one daytime accident during the previous two-year period should not prevent flashing operation from being implemented.

CHAPTER 6
SUPPLEMENTAL RESEARCH ACTIVITIES

Although operations (delay) and safety (accidents) are the primary concerns associated with flashing operation of traffic signals, there are other factors which should be considered in a decision to implement flashing operation. These additional issues include electrical power consumption of flashing operation, driver behavior at intersections with flashing operation, and the relationship between 24-hour volumes and volumes during nighttime conditions. Each of these issues was studied specifically as it relates to flashing signals operation.

Electrical Power Consumption

One benefit of flashing signal operation is reduced electrical power consumption. The total amount of electrical power necessary to operate a traffic signal in the flashing mode is less than the power required for normal green-yellow-red operation. These savings are intuitive, because the Texas MUTCD (1) states that flashing signal lamps are illuminated for only one-half to two-thirds as long as lamps using normal operation. Previous studies (6, 28) have confirmed that flashing operation produces electrical power savings on the order of approximately 50 to 65 percent. Reduced power consumption translates into lower electricity bills for the public agency responsible for the signal. The following sections describe the objectives, procedures, results, and findings of the power consumption evaluation.

Objectives

It is clear that flashing signal operation is beneficial in terms of electrical consumption and the associated cost of operating the signal. However, it is difficult to quantify the magnitude of these benefits. Therefore, this task was undertaken to assist the traffic engineer in estimating potential environmental and monetary benefits, specifically those that result from reduced power consumption with flashing operation. The following objectives were identified for this research:

- Predict power savings due to flashing operation.
- Develop procedures for estimating the resulting monetary savings.

Evaluation Procedure

To estimate power savings due to flashing signal operation, the amount of power actually consumed by several signals during two different operating modes (i.e., normal and flashing operation) was measured. Five signalized diamond interchanges located on State Highway 6 Bypass in Bryan and College Station were selected for the evaluation. These provided power consumption data for a total of ten intersections. Typically, the signals at each of these ten intersections operates in the normal green-yellow-red mode using pretimed operation. However, the signals are placed in flash during late-night and early-morning operation (e.g., 10:00 pm to 7:00 am).

Power consumption was measured using a digital wattmeter provided by the Department of Electrical Engineering at Texas A&M University. This battery-operated, hand-held device allows the user to conduct instantaneous measurements of the amount of power used by an electrical circuit. Power consumption values, in kilowatts, are obtained when the wattmeter is attached to the circuit. An alternative to this method is to record actual meter readings for the signal over a given period of time; however, this approach is very time consuming, requiring several hours of observation and may not provide an acceptable level of precision to draw useful comparisons.

Two measurements were obtained at each signal. The first set of measurements was taken while the signal operated in its normal green-yellow-red mode. Because power consumption did not remain constant throughout one complete cycle, measurements were made for each signal phase. Using a stopwatch, the length of each signal interval, including change intervals, and the cycle length were measured. A power consumption reading was then obtained for each interval with the wattmeter.

The second set of measurements was taken while the signal operated in flash. The flash rate, defined as the number of flashes per minute, was measured. The wattmeter was used to determine power consumption. Power consumption varied as a function of the flash pattern, cycling between high and low readings as alternating approaches were shown their respective flashing indications.

Results

Given the power consumption value for a specified interval and the length of the interval, the power consumed by the signal, in kilowatt-hours, during the interval was calculated. The summation of these values over one complete cycle yielded the total power consumed during the cycle. Dividing by the cycle length and converting units allowed power consumption to be expressed as a rate, with units of kilowatt-hours per hour. This form is useful for calculating total power consumption when the signal operates in a given mode for a specified period of time (e.g., the signal operates in flash for eight hours each day). It is also used to compare power consumption under different operating scenarios. Table 6-1 indicates total power consumption and the rate of power consumption for the ten intersections studied for normal operation.

Table 6-1. Power Consumption for Normal Operation

Interchange		Total Power Consumed Per Cycle (kw-hrs)	Cycle Length (sec)	Rate of Power Consumption (kw-hrs/hr)
SH 6 Frontage Road at	Side			
SH 21	East	0.0287	70	1.477
	West	0.0289	70	1.485
FM 158	East	0.0331	80	1.491
	West	0.0349	80	1.571
FM 1179	East	0.0286	70	1.472
	West	0.0295	70	1.516
FM 60	East	0.0236	60	1.415
	West	0.0231	60	1.384
SH 30	East	0.0299	80	1.346
	West	0.0288	80	1.296

The rate of power consumption for a flashing signal was developed in a similar manner. As described previously, the power readings rendered by the wattmeter fluctuated cyclically between low and high values. All ten signals flashed at a rate of sixty flashes per minute, so it was reasoned that each signal would be illuminated for a period of one-half second each time the signal flashed. In other words, a lamp would be illuminated for a total of thirty seconds during one minute of flashing operation. The low and high readings obtained by the wattmeter corresponded to the illumination cycle of specific signal heads. If the signal is illuminated half of the time that it flashes and dark the remaining half, and if the low power reading corresponds to the time that the signal is not illuminated while the high value corresponds to the time that the signal is illuminated, then it would be appropriate to base the calculation of the rate of power consumption upon a simple average of the low and high meter readings. Table 6-2 presents the rate of power consumption for the ten signalized intersections during flashing operation.

Table 6-2. Power Consumption for Flashing Operation

Interchange		Rate of Power Consumption (kw-hrs/hr)
SH 6 Frontage Road at	Side	
SH 21	East	0.900
	West	0.850
FM 158	East	0.875
	West	0.915
FM 1179	East	0.860
	West	0.890
FM 60	East	0.845
	West	0.665
SH 30	East	0.685
	West	0.665

The magnitude of the power savings realized with flashing operation may be quantified by comparing the rate of power consumption for a signal operating in the normal green-yellow-red mode to the power consumption rate for a flashing signal. This comparison is presented in Table 6-3. On average, the amount of power consumed by the signal was reduced about 44 percent by placing the signal in flash. In other words, a flashing signal will require only 56 percent of the power necessary to operate the signal in green-yellow-red mode.

It is also worth noting that the power consumed during any given interval of normal signal operation closely corresponded to the total wattage of the signal lamps illuminated during that interval. In other words, the power consumed by a traffic signal can be closely estimated by calculating the energy consumed by the signal lamps. In general, the signal installations evaluated in this study contained eight, 12-inch (300 mm) signal heads with 150 watt lamps. Therefore, at any given point in time, at least 1200 watts of power (8 lamps × 150 watts/lamps) were being consumed. Several of the intersections also had one or more approaches with a protected leading or lagging left phase. During this time, an extra lamp was illuminated. The power consumed by the controller was found to be less than that consumed by a single lamp.

Table 6-3. Power Consumption Comparison for Normal and Flashing Operation

Interchange		Rate of Power Consumption (kw-hrs/hr)		Percent Savings
SH 6 Frontage Road at	Side	Normal Operation	Flashing Operation	
SH 21	East	1.477	0.900	39.1
	West	1.485	0.850	42.8
FM 158	East	1.491	0.875	41.3
	West	1.571	0.915	41.8
FM 1179	East	1.472	0.860	41.6
	West	1.516	0.890	41.3
FM 60	East	1.415	0.845	40.3
	West	1.384	0.665	52.0
SH 30	East	1.346	0.685	49.1
	West	1.296	0.665	48.7
Average		1.4453	0.8150	43.78
Standard Deviation		0.0837	0.1014	4.42

Cost Savings Prediction

The second objective of this task was to apply the results of the power consumption evaluation and develop a procedure to estimate potential monetary savings when a signal's operation is converted to flash. The power costs associated with flashing operation are predicted by Equation 6-1:

$$C_{flash} = 0.56\ (24 \times E_{normal} \times C_{electricity}) \qquad \textbf{(6-1)}$$

where

C_{flash} = Cost of electrical power for flashing operation ($/day).

E_{normal} = Rate of electrical power consumption for normal signal operation (kilowatt-hours/hour).

$C_{electricity}$ = Cost of electricity ($/kilowatt-hour).

If the signal's normal rate of power consumption and the cost of electricity are known, then Equation 6-1 predicts the cost of electricity to support flashing operation, assuming a 44 percent average reduction in power consumption. This cost is expressed in dollars per day of signal operation.

A variation of Equation 6-1 calculates the anticipated monetary savings attributed to reduced power consumption when a signal is placed in flash. If the signal's normal rate of power consumption and the cost of electricity are known, then Equation 6-2 predicts the amount of savings (e.g., the difference between the cost of normal operation and the cost of flashing operation) that may be expected, again assuming an average reduction in power consumption of 44 percent.

$$S_{flash} = 0.44\ (24 \times E_{normal} \times C_{electricity}) \qquad \textbf{(6-2)}$$

where S_{flash} = Anticipated monetary savings ($/day).
E_{normal} = Rate of electrical power consumption for normal signal operation (kilowatt-hours/hour).
$C_{electricity}$ = Cost of electricity ($/kilowatt-hour).

The magnitude of the reduction in power consumption assumed in Equations 6-1 and 6-2 was observed in the experiment described in the preceding section and agrees closely with other reported values of 50 to 65 percent savings. However, caution should be used when applying these equations and interpreting the results. It must be recognized that variations in signal equipment may result in less or perhaps greater savings than were observed in this evaluation. Furthermore, seasonal and climatic differences may also influence power consumption and cause results to differ from those reported here.

The number of signal lamps illuminated during normal and flashing operation has the greatest impact on the potential energy savings. The 50 to 65 percent energy use of flashing operation is based on changing from constant illumination of a single lamp in a signal head to flashing operation of a single lamp in a signal head. The energy savings will be greater for those installations where multiple lamps in a signal head are illuminated during the same phase interval (such as protected/permitted left-turn or a double red indication for the left turn signal head). Therefore, Equation 6-3 can also be used to estimate the power savings of flashing operation.

Example of Formula Application

The following hypothetical situation is provided to illustrate the application of the two equations presented above in estimating the power costs and the savings when a signal is placed in flash. A signal currently using 24-hour normal operation is being considered for flashing operation between midnight and 6:00 am. Utility records indicate that electrical power is consumed by this signal at an average rate of 1.5 kilowatt-hours per hour. Currently, the city is paying \$0.10 per kilowatt-hour for electricity. The cost of power for flashing operation, expressed on a per day basis, is estimated by applying Equation 6-1.

$$C_{flash} = (\ 0.56\ ) \left(\frac{24\ hr}{day} \right) \left(\frac{1.5\ kw\text{-}hr}{hr} \right) \left(\frac{\$0.10}{kw\text{-}hr} \right) = \$2.02\ /\ day$$

This value can be manipulated to determine the yearly cost of power for flashing operation, recognizing that the signal will only flash six hours per day (12:00 mid to 6:00 am).

$$\left(\frac{\$2.02}{day} \right) \left(\frac{6\ hours/day}{24\ hours/day} \right) \left(\frac{365\ days}{year} \right) = \$184.33\ /\ year$$

The cost of power consumed by the signal in normal operation during the same six-hour period, expressed on a per year basis, is determined by.

$$\left(\frac{24\ hours}{day} \right) \left(\frac{1.5\ kw\text{-}hr}{hr} \right) \left(\frac{\$0.10}{kw\text{-}hr} \right) \left(\frac{6\ hours/day}{24\ hours/day} \right) \left(\frac{365\ days}{year} \right) = \$328.50/year$$

Thus, the yearly monetary savings due to the conversion to flashing operation between 12:00 mid and 6:00 am is the difference between these two values.

$$\$328.50\ -\ \$184.33\ =\ \$144.17.$$

The monetary savings calculated above can also be determined on a per day basis by application of Equation 6-2.

$$S_{flash} = (\ 0.44\ ) \left(\frac{24\ hours}{day} \right) \left(\frac{1.5\ kw\text{-}hr}{hr} \right) \left(\frac{\$0.10}{kw\text{-}hr} \right) = \$1.58\ /\ day$$

Converting to express this as a yearly savings yields.

$$\left(\frac{\$1.58}{day}\right)\left(\frac{6\ hours/day}{24\ hours/day}\right)\left(\frac{365\ days}{year}\right) = \$144.17\ /\ year$$

As an alternative, the power consumption of the signal in normal operation could be calculated from the total number of lamps illuminated during a cycle. For instance, if the signal has three phase operation with a protected left-turn operated by a separate signal head, then there are three signal heads on each major street approach and two signal heads on each minor street approach, for a total of 10 signal heads. If 150 watt lamps are used in each signal head, then the total power consumption of the signal lamps would be 1,500 watt-hour/hour, or 1.5 kilowatt-hour/hour, which was used in the previous calculations. Pedestrian signals should also be considered as these signals are not illuminated at night.

To summarize, conversion of the signal to flashing operation between the hours of midnight and 6:00 am will produce savings of approximately $144 per year. The annual cost of electrical power to support flashing operation will be about $184, versus about $328 for normal operation during the same six-hour period.

Driver Behavior

Driver behavior at a flashing traffic signal has not been well documented in the past, despite the fact that certain types of behavior may lead to accidents. Undocumented observations of flashing operation by members of the research team indicated that some drivers do not know the meaning of the flashing yellow indication. These drivers are confused when they approach a flashing yellow signal and stop at the intersection. This increases the potential for rear-end accidents and has a significant negative impact on signal operations.

Another type of driver behavior which may lead to accidents occurs at signals using normal operation during low-volume periods. If a driver approaching a steady red indication stops at an intersection and does not see any traffic on the cross-street, he may not be willing to wait for a green indication and will run the red indication and complete the desired maneuver. When this occurs, a signal using normal operation is actually operating as a flashing red signal for that approach.

As part of this study, driver behavior was observed by video taping traffic operations at signalized intersections using both flashing and normal operation. A total of seven intersections were filmed from midnight to 6:00 am. Three intersections are in the Bryan/College Station area, three intersections are in Bay City, and one intersection is in Wharton. These seven intersections consisted of two yellow/red flashing signals, a red/red flashing signal, two pretimed signals, and two actuated signals. The video camera was located so that traffic movements could be obtained for each approach, but not in view so as to distract motorists. The video was then observed in order to count turning movements, illegal maneuvers (violations), and pedestrian activity. Observations of nighttime signal operation identified the three types of driver behavior listed below.

- Drivers treat a pretimed and actuated signals as a stop controlled intersection, stopping at a steady red indication and then proceeding into the intersection before the indication changes to green.
- Drivers fail to come to a complete stop at a flashing red indication or fail to completely stop at a steady red before completing a turning maneuver.
- Drivers make a stop at a flashing yellow indication.

These types of driver behavior were also observed in the FHWA study (6). In that study, before-and-after violation rates were compared for the following changes in signal operation:

- Twenty-four hour normal operation changing to nighttime yellow/red flashing operation.
- Twenty-four hour normal operation changing to nighttime red/red flashing operation.
- Nighttime yellow/red flashing operation changing to nighttime red/red flashing operation.

Each intersection was observed for one hour. Violations were defined as a vehicle entering the intersection on a red phase. For flashing operation, a violation was defined as a vehicle not making a stop at a flashing red signal, although vehicles making slow rolling actions were considered as stopped and, hence, were not classified as violators.

The FHWA study (6) found that at intersections where signal operation changed from normal operation to yellow/red flashing operation, the violations on the major street with the flashing yellow indication went down and violations went up on the minor street with the flashing red indication. Corresponding patterns were found when normal operation changed to red/red flashing operation and when yellow/red flashing operation changed to red/red flashing operation. For both the major and minor streets, violations were found to be higher with red/red flashing operation than with either alternative. The results of the FHWA violation analysis are shown in Table 6-4.

Table 6-4. Violations Per Hundred Vehicles at Flashing Study Locations (6)

Street	Condition (Daily Signal Operation)	Change in Signal Operation		
		Normal to Yellow/Red Flash	Normal to Red/Red Flash	Yellow/Red Flash to Red/Red Flash
Major Street	Normal	1	2	0
	Flashing	0	5	3
Minor Street	Normal	1	2	1
	Flashing	6	3	4
Both Streets	Normal	1	2	1
	Flashing	1	4	3
No. of Intersections		81	6	2

Another FHWA study conducted in 1989 (43) evaluated driver compliance with all types of traffic control devices. Field observations of traffic signal compliance found that about 0.9 percent of drivers illegally entered intersections controlled by traffic signals. The same study also conducted a survey of drivers to determine attitudes toward violations. The survey found that 3.3 percent of typical drivers admitted to running a red signal indication on a daily basis.

The results of this TTI study on driver behavior is not as extensive as either of the FHWA studies (6, 43). Because the TTI study sites did not make any signal control change, comparisons between normal and flashing signal operation could not be made for the same intersection. However, an analysis was made between intersections operating as pretimed, flashing, and actuated.

Observations at the study sites indicate that violation rates are lower for yellow/red flashing operation than either pretimed or actuated signal operation. This observation would be expected due to the difference in the amount of delay experienced by drivers approaching a flashing signal as compared to a signal with normal operation. Tables 6-5 and 6-6 illustrates the violation rates observed in the TTI study for the Bryan/College Station and Bay City/Wharton locations. Several (although not the majority) of the violations were created by emergency type vehicles in an apparent non-emergency mode of operation. The violations showed a great deal of variability between the various locations and types of traffic control.

It is worth noting that violations were committed at all four types of signal operations. The most serious of the violations was the failure to come to a complete stop for a steady or flashing red indication. In general, these violations are not likely to be serious due to the extremely low volumes present during nighttime hours.

Table 6-5. Driver Behavior - Bryan/College Station Location

Signal Operation	Street	Violations/100 vehicles
Pretimed	Major Minor	1.9 2.4
Yellow/Red Flash	Major Minor	1.8 0.1[1]
Actuated	Major Minor	1.8 0.0

Note: [1] Denotes a vehicle making a complete stop at a flashing yellow signal, although this maneuver is not a violation of any law.

Table 6-6. Driver Behavior - Bay City/Wharton Locations

Signal Operation	Street	Violations/100 vehicles
Pretimed	Major Minor	5.98 1.32
Yellow/Red Flash	Major Minor	0.68 6.00
Red/Red Flash	Major[1] Major[1]	2.33 6.15
Actuated	Major Minor	0.72 12.30

Note: [1] Denotes that both arterials are classified as "Major" because of equal functional classification.

Nighttime Volume Data

Any analysis of flashing signal operation requires traffic volume data in order to measure the effectiveness of the signal. Two forms of volume data have been used in previous evaluations of flashing signal accidents: traffic volumes and volume ratios. Ideally, the hourly volume for the time of the accident should be used. However, the volume for a given hour may not always be available. Therefore, the volume data collected for this study were analyzed to determine the relationship between the Average Daily Traffic (ADT) and the nighttime hourly volume.

Typically, flashing signal operation is used during late-night and early-morning periods, when traffic volumes are significantly lower than volumes at other times of the day. Many of the guidelines for flashing operation developed in previous research studies (5, 6, 7, 8, 9, 10) are based on an hourly volume or a volume ratio. The traffic engineer may not know the traffic volume during the late-night or early-morning hours at the intersection which is being considered for flashing operation. However, the traffic engineer typically knows the ADT for at least one, and often both, intersecting roadways. Therefore, if a relationship between the ADT and the nighttime hourly volume can be determined, the guidelines for flashing operation will be easier to apply.

Hourly traffic volumes were obtained from the cities of Austin, Beaumont, Dallas, and Houston. The analysis considered a total of 242 observations, and each observation consisted of hourly traffic volumes for a specified roadway direction, location, and date.

The hourly volumes were summed to obtain a 24-hour ADT. The ADTs for the 242 observations ranged from a low of approximately 500 vehicles per day (vpd) to a high of nearly 39,000 vpd. A ten-hour study period, beginning at 9:00 pm and concluding at 7:00 am, was selected for the analysis. The hourly traffic volumes were divided by the ADT in order to determine each hour's contribution to the 24-hour ADT. This contribution is expressed as a percentage of the 24-hour ADT. For example, a one-hour volume of 500 vehicles at a count location with a 24-hour ADT of 10,000 vpd would represent a contribution of 5 percent for that particular hour.

It was predicted that the 24-hour ADT would impact hourly volume percentages. In other words, the percentage of ADT for a given hour would vary between two or more sites as a function of the 24-hour ADT at those sites. To account for this effect, an ADT classification was established. The following limits define six ADT classes: (1) ADT ≤ 4,999; (2) 5,000 to 9,999 ADT; (3) 10,000 to 14,999 ADT; (4) 15,000 to 19,999 ADT; (5) 20,000 to 24,999 ADT; and (6) ADT ≥ 25,000. Each of the 242 observations was assigned to one of the six classifications based upon its ADT. The number of observations within each ADT class was as follows: Group 1 - 56 observations; Group 2 - 54 observations; Group 3 - 53 observations; Group 4 - 45 observations; Group 5 - 26 observations; and Group 6 - 8 observations.

Within each of the six ADT classes, the mean hourly percentage of the ADT was calculated for each hour of the ten-hour study period. The standard deviation and the range of values for each hour were also determined. The results of this procedure are illustrated in the accompanying tables (Tables 6-7 through 6-13).

Table 6-7. Relationship Between ADT and Nighttime Hourly Volumes for 0 to 4,999 ADT

Hour	Percent of 24-Hour Traffic Volume[1]			
	Minimum	Mean	Maximum	Standard Deviation
9:00 to 10:00 pm	0.3	3.6	7.2	1.20
10:00 to 11:00 pm	0.1	2.2	4.4	0.76
11:00 pm to 12:00 mid	0.1	1.3	3.1	0.55
12:00 to 1:00 am	0.1	0.7	1.9	0.34
1:00 to 2:00 am	0.0	0.4	1.0	0.20
2:00 to 3:00 am	0.0	0.3	0.9	0.19
3:00 to 4:00 am	0.0	0.2	4.1	0.54
4:00 to 5:00 am	0.0	0.4	12.8	1.69
5:00 to 6:00 am	0.1	0.8	9.9	1.33
6:00 to 7:00 am	0.5	2.8	8.9	1.72

Note: [1]Based on 56 observations.

Table 6-8. Relationship Between ADT and Nighttime Hourly Volumes for 5,000 to 9,999 ADT

Hour	Percent of 24-Hour Traffic Volume[1]			
	Minimum	Mean	Maximum	Standard Deviation
9:00 to 10:00 pm	1.1	3.2	5.2	1.00
10:00 to 11:00 pm	0.9	2.3	5.7	0.81
11:00 pm to 12:00 mid	0.3	1.4	3.3	0.57
12:00 to 1:00 am	0.3	0.8	2.0	0.39
1:00 to 2:00 am	0.1	0.4	1.3	0.23
2:00 to 3:00 am	0.1	0.3	0.9	0.17
3:00 to 4:00 am	0.0	0.2	0.5	0.11
4:00 to 5:00 am	0.0	0.3	0.9	0.16
5:00 to 6:00 am	0.0	0.7	3.0	0.51
6:00 to 7:00 am	0.4	2.8	8.4	1.90

Note: [1]Based on 54 observations.

Table 6-9. Relationship Between ADT and Nighttime Hourly Volumes for 10,000 to 14,999 ADT

Hour	Percent of 24-Hour Traffic Volume[1]			
	Minimum	Mean	Maximum	Standard Deviation
9:00 to 10:00 pm	1.5	3.1	6.7	0.87
10:00 to 11:00 pm	1.1	2.2	4.5	0.57
11:00 pm to 12:00 mid	0.4	1.3	2.8	0.42
12:00 to 1:00 am	0.3	0.8	3.0	0.40
1:00 to 2:00 am	0.1	0.5	2.1	0.29
2:00 to 3:00 am	0.1	0.3	1.2	0.19
3:00 to 4:00 am	0.1	0.2	0.6	0.10
4:00 to 5:00 am	0.1	0.3	2.2	0.29
5:00 to 6:00 am	0.1	0.9	7.0	1.07
6:00 to 7:00 am	0.3	2.8	9.0	2.23

Note: [1]Based on 53 observations.

Table 6-10. Relationship Between ADT and Nighttime Hourly Volumes for 15,000 to 19,999 ADT

Hour	Percent of 24-Hour Traffic Volume			
	Minimum	Mean	Maximum	Standard Deviation
9:00 to 10:00 pm	2.3	3.4	5.2	0.71
10:00 to 11:00 pm	1.7	2.4	3.5	0.50
11:00 pm to 12:00 mid	0.9	1.5	3.0	0.46
12:00 to 1:00 am	0.6	1.0	2.0	0.33
1:00 to 2:00 am	0.3	0.6	1.6	0.26
2:00 to 3:00 am	0.2	0.5	1.0	0.18
3:00 to 4:00 am	0.2	0.3	0.6	0.10
4:00 to 5:00 am	0.1	0.4	0.7	0.15
5:00 to 6:00 am	0.3	1.1	2.5	0.56
6:00 to 7:00 am	0.7	4.1	9.1	2.29

Note: [1]Based on 45 observations.

Table 6-11. Relationship Between ADT and Nighttime Hourly Volumes for 20,000 to 24,999 ADT

Hour	Percent of 24-Hour Traffic Volume[1]			
	Minimum	Mean	Maximum	Standard Deviation
9:00 to 10:00 pm	2.2	3.4	5.7	0.80
10:00 to 11:00 pm	1.4	2.4	5.8	0.84
11:00 pm to 12:00 mid	0.8	1.6	6.8	1.10
12:00 to 1:00 am	0.5	1.2	8.1	1.44
1:00 to 2:00 am	0.3	0.8	8.8	1.64
2:00 to 3:00 am	0.0	0.7	8.2	1.53
3:00 to 4:00 am	0.2	0.6	7.9	1.49
4:00 to 5:00 am	0.2	0.7	7.5	1.41
5:00 to 6:00 am	0.6	1.8	7.7	1.62
6:00 to 7:00 am	1.0	4.3	10.0	2.33

Note: [1]Based on 26 observations.

Table 6-12. Relationship Between ADT and Nighttime Hourly Volumes for 25,000 ADT and Greater

Hour	Percent of 24-Hour Traffic Volume[1]			
	Minimum	Mean	Maximum	Standard Deviation
9:00 to 10:00 pm	2.4	3.9	6.5	1.54
10:00 to 11:00 pm	1.6	3.3	7.1	1.97
11:00 pm to 12:00 mid	0.9	2.9	8.3	2.76
12:00 to 1:00 am	0.4	2.5	8.2	3.11
1:00 to 2:00 am	0.3	2.0	7.6	2.97
2:00 to 3:00 am	0.2	0.9	7.1	2.83
3:00 to 4:00 am	0.2	1.8	6.7	2.79
4:00 to 5:00 am	0.2	1.9	6.2	2.70
5:00 to 6:00 am	0.4	2.5	6.2	2.19
6:00 to 7:00 am	1.7	5.2	7.0	2.20

Note: [1]Based on 8 observations.

Table 6-13. Relationship Between ADT and Nighttime Hourly Volumes by ADT Classification

Hour	ADT Classification						Average
	0 to 4,999	5,000 to 9,999	10,000 to 14,999	15,000 to 19,999	20,000 to 24,999	25,000 +	
9:00 to 10:00 pm	3.6%	3.2%	3.1%	3.4%	3.4%	3.9%	3.4
10:00 to 11:00 pm	2.2%	2.3%	2.2%	2.4%	2.4%	3.3%	2.3
11:00 pm to 12:00 mid	1.3%	1.4%	1.3%	1.5%	1.6%	2.9%	1.4
12:00 to 1:00 am	0.7%	0.8%	0.8%	1.0%	1.2%	2.5%	0.9
1:00 to 2:00 am	0.4%	0.4%	0.5%	0.6%	0.8%	2.0%	0.6
2:00 to 3:00 am	0.3%	0.3%	0.3%	0.5%	0.7%	0.9%	0.4
3:00 to 4:00 am	0.2%	0.2%	0.2%	0.3%	0.6%	1.8%	0.3
4:00 to 5:00 am	0.4%	0.3%	0.3%	0.4%	0.7%	1.9%	0.4
5:00 to 6:00 am	0.8%	0.7%	0.9%	1.1%	1.8%	2.5%	1.0
6:00 to 7:00 am	2.8%	2.8%	2.8%	4.1%	4.3%	5.2%	3.3
Total	12.7%	12.4%	12.4%	15.3%	17.5%	26.9%	14.0

The six ADT classes were compared using SAS (Statistical Analysis Software). The results of this analysis confirmed the prediction that hourly ADT percentages at different sites vary as a function of the ADT class. In general, locations with higher ADTs were observed to experience a greater percentage of ADT using the facility during late-night and early-morning hours than locations with lower ADTs. This study seemed to indicate that this effect is noticed at locations with ADTs greater than about 15,000 vpd. Therefore, estimates of the number of vehicles using a particular roadway or intersection during late-night or early-morning hours of operation are most accurate when the ADT classification is a factor in their development.

Traffic volumes at a typical location during late-night and early-morning hours of operation might be expected to follow a fairly predictable trend. This trend reflects the relative amount of activity which is observed during this period. Such a trend was apparent in the volume data collected for this study. From 9:00 pm until 1:00 am, hourly traffic volumes decreased steadily. For the next four hours, from 1:00 am until 5:00 am, the volumes remained fairly constant each hour. In fact, a statistical comparison of the hourly ADT percentages revealed that they are essentially the same for each of the four hours during this period. After 5:00 am, the hourly volumes began to increase.

The results of a previous study (44) indicate that 3.6 percent of the 24-hour traffic volume occurs between midnight and 6:00 am. Another way of viewing this is that, on the average, 0.6 percent of the ADT will occur each hour during this period of time. The findings of this study compare favorably with those of the previous research. Analysis of these traffic volumes indicated that approximately 3.7 percent of the 24-hour ADT occurs between 12:00 and 6:00 am, and that just slightly more than 0.6 percent occurs each hour.

Conclusions

The supplemental evaluations of flashing signal operation identified several pieces of information which can be useful in making a decision on the use of nighttime flashing operation. The information relates to the electrical power and monetary savings that can be realized by changing to flashing operation, observations of driver behavior at traffic signals during nighttime low-volume conditions, and the relationship between nighttime volumes and the 24-hour volume.

The analysis of electrical power consumption revealed that power consumption of flashing signal operation is about 56 percent of normal operation. For a typical signalized intersection with 6 hours of flashing operation per day, this equates to about $150 of savings per year. The actual savings depend upon the hours of flashing operation and the illumination of signal lamps during normal and flashing operation.

Observations of driver behavior found low compliance with traffic signals during low-volume nighttime periods. Violation rates as high as 12 percent were found at one location. More common violation rates were about 2 percent of the entering traffic. No patterns were identified for the type of violation, the type of traffic control, or the classification of the roadway.

The analysis of nighttime traffic volumes identified various relationships between the nighttime volumes and the 24-hour volumes. The total volume between 9:00 pm and 7:00 am ranges between 12 and 15 percent of the ADT. Hourly volumes between midnight and 5:00 am typically range between 0.2 and 1.0 percent of the ADT.

CHAPTER 7
CONCLUSIONS AND GUIDELINES

Traffic signals typically operate in a normal (green-yellow-red) mode during most of the day. However, there are some situations in which flashing operation can be used as an effective alternative to normal operation, if the appropriate circumstances are present. This research study was conducted to evaluate flashing traffic signal operation and determine when and how it can be effectively used, particularly in low-volume, nighttime conditions. A number of different issues were analyzed as part of the study effort. The major study activities included a review of previous research, a review of current practice which included several surveys of practicing professionals, an analysis of the operational effects of flashing operation, an analysis of the accident impacts of flashing operation, measurement of the power savings resulting from flashing operation, evaluation of driver behavior at flashing signals during nighttime hours, and an analysis of the relationships between 24-hour and nighttime hourly traffic volumes. The key findings of each of these activities are described below.

- **Literature Review** - There have been numerous studies of flashing signal operation. In general, these studies have focused upon the relationship between flashing operation and accidents. Most of these studies have found that right-angle accidents occur more frequently when flashing operation is used. The potential for accidents during yellow/red flashing operation seems to be greater when the volume ratio is less than about 3 or 4.
- **Current Practice** - Flashing operation is widely used in many agencies, although there are few written guidelines for implementing flashing operation. The most common uses of flashing operation are for emergency flashing, signal installation, signal removal, railroad preemption, and during low-volume conditions.
- **Operational Analysis** - The use of yellow/red flashing operation can reduce vehicular delay by as much as two-thirds over signals using normal operation. However, the traffic conditions which are present during low-volume conditions typically mean that the actual delay savings per vehicle is less than 10 seconds.
- **Accident Analysis** - Previous research findings indicate that intersections using flashing operation tend to have higher accident frequencies during the periods that flashing operation is being used. The accident analysis of this study found that intersections with zero daytime accidents in a two-year period were found to have zero accidents when

converted to flashing operation. The accident analysis was not able to identify any statistically significant relationship between nighttime accidents during normal and flashing operation.

- **Power Savings Analysis** - The analysis indicated that about $150 of electrical power could be saved each year by operating a typical traffic signal in the flashing mode for 6 hours a day. This amount does not appear to be sufficient to be the primary justification for using flashing operation.
- **Driver Behavior** - Violations of flashing signal indications do not appear to be any higher than violations of signal indications in normal operation.
- **Traffic Volume Relationships** - The volume relationships shown in Tables 6-7 through 6-13 can be used to estimate hourly volumes during nighttime periods.

While there is some agreement about certain aspects of flashing operation, previous research and the experiences of practicing professionals do not always agree. It appears that the effective use of flashing operation is highly dependent upon the specific circumstances of the situation in which it is being used. As a result, it is difficult, if not impossible to develop definitive flashing guidelines which can be effectively applied to all situations. **The decision to use flashing operation continues to be one which requires a great deal of engineering judgement.**

There are many different situations in which flashing operation may provide an effective alternative form of traffic signal control. This chapter contains guidelines which should be considered in evaluating the use of flashing traffic signal operation in the following circumstances:

- Flashing Operation during Nighttime, Low-Volume Conditions.
- Flashing Operation Prior to Signal Turn-On.
- Flashing Operation Prior to Signal Removal.
- Flashing Operation Initiated by the Conflict Monitor or Maintenance Activities.
- Flashing Operation during Adverse Weather Conditions.
- Flashing Operation at Railroad-Highway Grade Crossings.
- Flashing Operations in School Areas.

Guidelines for Flashing Operation

The findings of this research do not indicate any particular circumstances where it is clearly advantageous to use flashing operation instead of normal operation. Instead, the study findings indicate that the decision to implement flashing operation continues to be one which relies heavily on the use of engineering judgement to evaluate the various factors which impact the use of flashing operation at a traffic signal. Although engineering judgement is the primary factor which should affect the decision to implement or remove flashing operation in these situations, this research study has developed a number of guidelines or procedures that can be used to assist the traffic engineer in making a decision. These guidelines should be considered in the decision-making process, but the engineer should recognize that conditions may be present at any given intersection which may lead the engineer to a decision which is contrary to the guidelines described herein. Furthermore, it should be recognized that some of these guidelines have not been tested in actual practice.

In general, the findings of this research indicate that flashing operation should not generally be used unless an engineering study of the conditions indicate that flashing operation would be of greater benefit than normal operation. It is worth noting that for some of these conditions, flashing operation is the only practical signal operation available for use. Some of the circumstances in which flashing operation may be more advantageous than normal operation include:

- During preemption at railroad-highway grade crossings.
- Prior to initial installation or signal removal.
- As the result of the conflict monitor being activated.
- During maintenance or construction activities.
- During certain low-volume conditions.

The guidelines described in this chapter include detailed descriptions of the guidelines and explanations of why the guidelines should be considered. Flowcharts are also provided to summarize the key factors and provide a logical thought process for making a decision on flashing operation. It should be noted that the Texas MUTCD in use at the time these guidelines were developed was the 1980 edition with Revisions 1 through 4. Future revisions to the Texas MUTCD could affect the manner in which these guidelines are used.

General Guidelines for Flashing Signal Operation

There are some guidelines that apply to all circumstances in which flashing operation may be used. As a result, these guidelines should be considered anytime the use of flashing operation is being evaluated.

- **Texas MUTCD Principles.** Flashing signal operation should comply with the principles contained in the Texas MUTCD (1). These principles are grouped together in Appendix E for easy review. Some of the MUTCD principles are also repeated in the guidelines contained in this chapter.
- **Mode of Flashing Operation.** The decision to use yellow/red or red/red flash should be based on the delay and accident impacts. The operational analysis conducted for this study indicated that yellow/red flashing operation is most effective when the volume ratio is three or more. At ratios below three, red/red flashing operation results in lower delay. Several previous research studies have also found that accidents tend to increase as the volume ratio decreases. Most of these studies have indicated that care should be exercised when the volume ratio drops to a range between three and four. Based on these findings, the following guidelines should be considered in the selection of the flashing mode, *unless the guidelines for specific types of flashing operation indicate otherwise:*
  - ▸ Yellow/red flashing operation should be considered if the volume ratio is three or more unless adequate sight distance is not available.
  - ▸ Red/red flashing operation should be considered if either of the following conditions exist:
    - The volume ratio is less than three.
    - Adequate sight distance is not available.
- **Adequate Sight Distance.** Sight distance should be checked at all intersections where flashing operation is used. If yellow/red flashing operation is to be used, the intersection sight distance should meet the requirements set forth for Case III in the AASHTO Green Book (16). If the proper sight distance is not available, then red/red flashing operation should be used.
- **Accident Experience.** If the total number of accidents during the most recent two-year period of normal operation is one or less, then nighttime flashing operation can be considered as an alternative control strategy. The accident analysis conducted for this

study indicated that although flashing operation as a whole typically causes an increase in accidents, intersections with low accident experiences in normal operation also have low accident experiences in flashing operation. The research was not able to determine a statistically significant relationship between nighttime accidents during normal operation and nighttime accidents during flashing operation.

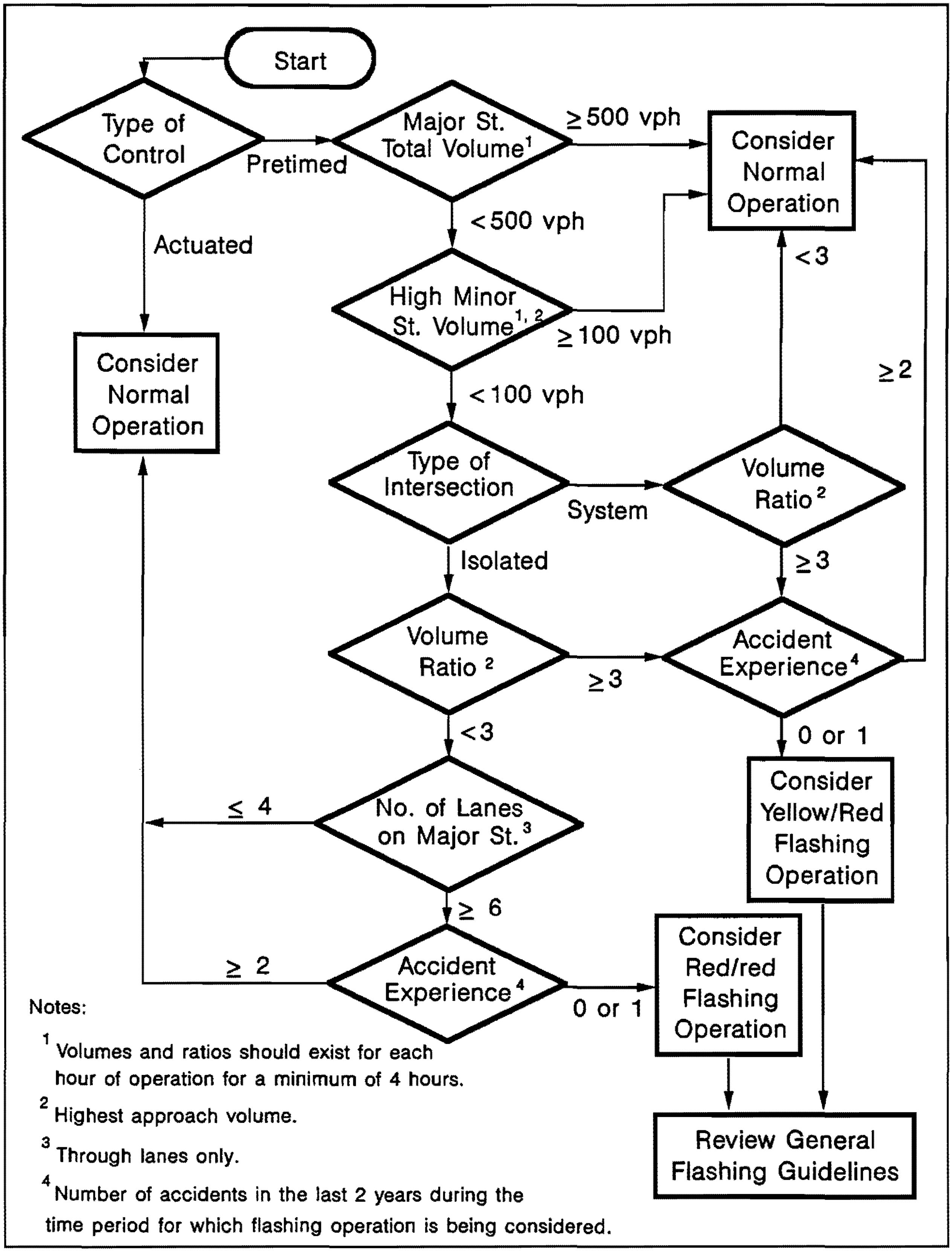
- **Time of Flashing Operation.** When flashing operation is used on a regularly scheduled basis at several intersections in an area, flashing operation should start and end at the same time for all intersections.
- **Flashing Compatibility.** If more than one type of flashing operation (such as low-volume and emergency flashing) is used at a single intersection, the compatibility should be checked to make sure that all types use the same flashing mode (yellow/red or red/red). This typically means that emergency flashing should use the same mode as the other types of flashing operation at the intersection. This guideline is intended to reduce the possibility that a driver can encounter two different types of flashing operation during the same day.
- **Education.** Educational efforts should be undertaken to improve driver knowledge of flashing signal indications. Potential methods of improving driver knowledge include increasing the emphasis in driver education/defensive driving courses and/or including flashing signal operations in a series of public service announcements on traffic control devices.
- **Left-Turn Signal Head.** Section 4B-6 of the Texas MUTCD (1) indicates that a left-turn signal head may use a flashing yellow or flashing red indication. If the color of the flashing indication in the left-turn signal head is different from that of the through lanes, then the left-turn signal head must be "*adequately shielded or positioned so that through traffic on the approach will not be exposed to substantial visual conflict from the left-turn signal indications*" (1).
- **Flashing of Left-Turn Signal Head.** If the left-turn signal head uses a flashing red indication while the signal head for through movements uses a flashing yellow, the two indications should be flashed alternately. Although this issue was not investigated in the study, the guideline is based on the philosophy that indications of different colors should not be shown simultaneously.
- **Volume Ratios.** In the absence of hourly volume data, the ratio of major to minor street traffic volume can be determined from the ADT for each street.

- **Pedestrian Signals.** Pedestrian signals should not be illuminated when the traffic control signal is using flashing operation.

Guidelines for Flashing Operation during Nighttime, Low-Volume Conditions

The majority of this study effort was focused upon the analysis of flashing operation during low-volume conditions as they typically occur during late-night and early-morning time periods. The following guidelines have been developed to assist the traffic engineer in deciding whether flashing operation should be used at a given intersection. The thought process for using these guidelines is indicated by the flowchart shown in Figure 7-1.

- **Actuated Traffic Signal.** If a traffic signal is capable of operating in the actuated mode, then flashing operation generally should not be used as a control strategy during low-volume conditions. The delay resulting from actuated operation is not significant enough compared to flashing operation to justify the use of flashing operation.
- **Pretimed Traffic Signal.** In general, flashing operation can be considered at an intersection if all of the following conditions are present for yellow/red or red/red flashing operation:
  - ▸ *Yellow/Red Flashing Operation:*
    - Major street two-way volume is less than 500 vph.
    - Minor street higher approach volume is less than 100 vph.
    - Major to minor street volume ratio is three or more.
    - The total number of accidents at the intersection during the preceding two years of normal signal operation is one or less.
  - ▸ *Red/Red Flashing Operation:*
    - Major street two-way volume is less than 500 vph.
    - Minor street higher approach volume is less than 100 vph.
    - Major to minor street volume ratio is less than three.
    - The total number of accidents at the intersection during the preceding two years of normal signal operation is one or less.
    - It is an isolated intersection (no signalized intersection within one-half mile (800 meters).
    - There are six or more through lanes on the major street.



Notes:

[1] Volumes and ratios should exist for each hour of operation for a minimum of 4 hours.

[2] Highest approach volume.

[3] Through lanes only.

[4] Number of accidents in the last 2 years during the time period for which flashing operation is being considered.

Figure 7-1. Flowchart for Implementing Flashing Operation during Low-Volume Conditions

- ▸ *General Guidelines.* Before low-volume, nighttime flashing operation is implemented at an intersection, the general guidelines for all types of flashing operation should also be checked.
- ▸ *Length of Flashing Operation.* In general, flashing operation should be used for those hours which meet the criteria described for each type of flashing operation. However, in order to avoid constant changing from flashing to normal operation and vice versa, flashing operation should be implemented only when the appropriate criteria are present for at least four hours.

Guidelines for Flashing Operation for Other Circumstances

In addition to the use of flashing operation for low-volume conditions, there are other circumstances in which flashing operation may be appropriate. The following paragraphs contain a few guidelines for the use of flashing operation during these conditions. It should be noted however, that these guidelines are based on engineering judgement, findings of previous research, and/or current policies/guidelines and were not the result of specific activities in this research study.

Flashing Operation Prior to Signal Turn-On

The operation of a new traffic signal adds a new element of control to the highway environment. Despite the fact that the signal may have been under construction for a period of weeks or months, the driving public requires an acclimation period following the signal turn-on. The needs of this acclimation period can best be served by placing the signal in flashing operation. The following factors should be considered when a signal is placed in flashing operation following the completion of signal construction.

- The mode of flashing operation selected for installation flashing should be based on the type of traffic control present prior to signal turn-on.
  - ▸ Red/red flashing operation should be used if the intersection used 4-way or multi-way stop sign control.
  - ▸ Yellow/red flashing operation should be used if the intersection used 2-way stop control or yield control.

- A new traffic signal should typically operate in the flashing mode for an extended period of time prior to the commencement of normal signal operation. There are no guidelines or recommended practices indicating the duration of flashing operation prior to normal signal operation. The flashing period can be anywhere from several hours to several days. Exceptions include situations in which an intersection beacon was in use at the intersection prior to normal signal operation and during periods of inclement weather.
- The conversion from flashing to normal operation at a newly installed traffic signal should not normally occur during the morning or evening peak periods.

Flashing Operation Prior to Signal Removal

On occasions, traffic conditions at a signalized intersection change such that the signal may no longer be needed. When a decision is made to remove a traffic signal, a period of time is needed for drivers to transition from signal control to the new type of control. During this transition period, the traffic signal should be operated in the flashing mode. If traffic operations or accident history during this period of flashing operation indicate the need to return the signal to normal operation, it can be done with a minimum of expense. The following factors should be considered when placing a signal in flashing operation prior to removal of the signal.

- A traffic signal planned for removal should be operated as a flashing signal for an extended period of time following the cessation of normal signal operation. A FHWA publication (45) recommends that the flashing period should be no less than 30 days long.
- The mode of flashing operation prior to signal removal should be selected on the basis of the type of control to which the intersection is being converted. Red/red flashing operation should be used for multi-way stop control and yellow/red flashing operation should be used for two-way stop or yield control.
- Stop signs should be installed on approaches to which a flashing red indication is displayed.
- The following FHWA publications contain additional information on the removal of traffic signals: *User Guide for Removal of Not Needed Traffic Signals* (45) and *Criteria for Removing Traffic Signals* (46).

Flashing Operation Initiated by the Conflict Monitor or Maintenance Activities

Emergency flashing is initiated when the conflict monitor in the signal detects a problem with the signal, or emergency flash may be manually induced. Because emergency flashing occurs on a random, and hopefully infrequent, basis, the selection of the flashing mode should be based on the mode used for other types of flashing operation expected to occur at an intersection. The following guidelines should be considered for emergency flashing operation.

- All signal controllers should have a conflict monitor which will initiate flashing operation if a problem is detected with the signal operation.
- Emergency flashing operation should use the same mode of flashing operation that is used for other types of flashing operation at the same intersection.
- The expected response time of police and maintenance personnel should be considered in the selection of red/red emergency flashing operation. If queues and delays during the expected response time would exceed an acceptable level, consideration should be given to the use of yellow/red flashing operation.
- If flashing operation will not be used for any other purpose at a given intersection, the mode of emergency flashing operation should be selected in the manner described for **Mode of Flashing Operation** under the **General Guidelines for Flashing Signal Operation**. In some cases, it may be desirable to select red/red flashing operation for emergency flashing operation due to the safety factor which it provides to maintenance personnel.

Flashing Operation during Adverse Weather Conditions

The survey of adverse weather signal operation did not reveal any consistent practices for the use of flashing operation during periods of adverse weather. In general, the use of flashing operation during periods when ice or snow are on the ground should be considered on an intersection-by-intersection basis.

Flashing Operation at Railroad-Highway Grade Crossings

The following guidelines should be considered when deciding whether to use flashing signal operations at a signal near a railroad-highway grade crossing.

- Railroad preemption should be considered if the intersection is within 200 feet (60 meters) of the railroad tracks. Preemption may be appropriate at intersections greater than 200 feet (60 meters) from the railroad-highway grade crossing in some circumstances.
- If the major street is parallel to the railroad tracks, then a flashing yellow indication can be displayed to the major street and a flashing red indication can be displayed to the minor street. However, if the railroad crossing is not protected by gates, turns from the major street toward the railroad tracks should be prohibited. This is necessary because the flashing yellow indication may lead the driver to think that a turn can be made across the tracks.
- If the major street crosses the railroad tracks, then red/red flashing is appropriate.
- If the volumes on the intersecting streets are approximately equal, then red/red flashing may be appropriate.
- The following references provide additional information about the operation of traffic signals near a railroad-highway grade crossing:
  - *Texas MUTCD* (1): Part VIII - Traffic Control for Railroad-Highway Grade Crossings
  - *Railroad-Highway Grade Crossing Handbook, 2nd Edition*, FHWA-TS-86-215 (47)
  - *Traffic Control Devices Handbook* (28).
- Part VIII of the *Traffic Control Devices Handbook* (28) contains drawings of the preemption sequences for various geometric configurations.

Guidelines for School Area Flashing

The following factors should be considered when deciding whether a traffic signal located near a school should be placed in flashing operation during a portion of the day.

- If a pretimed signal was warranted under the school warrant and does not meet any of the other warrants, then flashing operation of the signal during non-school periods may be considered as an alternative to normal operation.
- If a signal near a school area uses normal operation throughout the day, then actuated operation with pedestrian pushbuttons is desirable. Having an actuated pedestrian phase eliminates the need to provide pedestrian crossing time for every phase of the cycle. The pedestrian pushbuttons should be installed low enough so that young children can reach them, if the nearby school serves young children. The American with Disabilities Act

requires that pedestrian pushbuttons be no higher than 48 inches (1.2 meters) above the ground.

Recommended Changes to the Texas MUTCD

The research performed as part of this study has identified the following principles in the Texas MUTCD (1) which should be considered for change.

- The language in Section 4B-6 should be revised so that yellow/red flashing is not referred to as normal flashing.
- The language in Section 4B-6 should be revised to identify red/red flashing as an acceptable form of flashing operation.
- The existing language in Section 4B-18, shown in Table 7-1, should be replaced with the revised language shown in Table 7-1.

Table 7-1. Recommended Changes to Texas MUTCD Language

Existing Language	**Suggested Revised Language**
"When for a period of four or more consecutive hours of the late evening and/or early morning periods, any traffic volume drops to 50 percent or less of the stated volume warrants, pretimed traffic control signals should be placed on flashing operation rather than continue normal operation."	Pretimed traffic control signals may be placed in flashing operation when the following conditions exist: 1) Highest major street approach volume less than 250 vph. 2) Highest minor street approach volume less than 100 vph. 3) Ratio of major street to minor street volume of three or more. 4) Zero or one accident during preceding two years of 24-hour normal operation.

Source: Reference (1)

Recommendations for Future Evaluation

The research findings of this study indicate that the following issues should be evaluated in greater detail in future research efforts.

- The display of a flashing red indication to left-turn lane while a flashing yellow indication is displayed to through traffic has not been investigated. The following questions should be evaluated:

  - Is the use of a flashing red indication in the left-turn signal head an acceptable alternative to the use of a flashing yellow indication?
  - If a flashing red indication is acceptable, should the left-turn flashing red indication and the through flashing yellow indications be flashing simultaneously or alternately.
- The use of flashing operation at an intersection where a signal is being installed or removed should be evaluated in greater detail. There are no guidelines for the use of flashing operation prior to signal installation and limited guidelines for the use of flashing operation prior to signal removal.
- Informing drivers of right-of-way assignment at two-way stop-controlled intersections is an important element of intersection operation. This issue also relates to yellow/red flashing operation. The identification of treatments to inform drivers of right-of-way assignment is a major research effort in itself. However, the proposed flashing signal sign shown in Figure 7-2 could serve as a means of informing drivers of the right-of-way at a flashing signal. This sign should be evaluated for its effectiveness. If evaluations indicate that it effectively informs drivers of the flashing signal operation, then consideration should be given to using it where yellow/red flashing operation occurs on a regular basis.

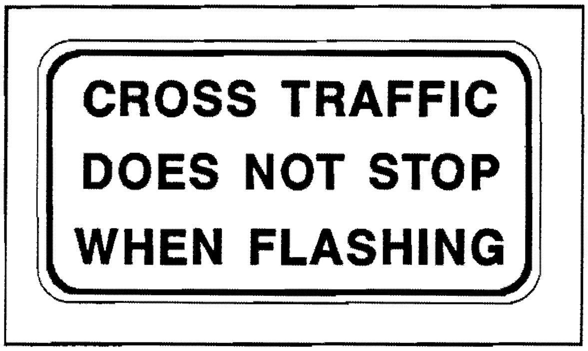


Figure 7-2. Sign for Flashing Operation

Overall Conclusions

This study of flashing signal operation was intended to evaluate the various factors which impact the use of flashing signal operation and to develop guidelines to assist TxDOT personnel and others in implementing flashing operation. A number of different activities were conducted as part of the study, and the results of the activities were used to develop the guidelines described in this chapter. In general, the use of flashing operation is appropriate under certain circumstances, and it may be the only effective alternative under other circumstances.

The majority of this research effort focused upon the use of flashing operation during low-volume, nighttime conditions. The findings were used to develop a flowchart for implementing nighttime flashing operation. Due to the operational flexibility provided by actuated signal control, flashing operation should only be used with pretimed signal control. Typically, flashing operation may be considered when the highest major street approach volume is less than 250 vph, the highest minor street approach volume is less than 100 vph, the volume ratio is three or more, and there have been no or one accident during the most recent two-year period.

In some situations, flashing operation provides the only effective means of controlling traffic when normal operation cannot be used. These situations include: signal installation and removal, emergency flash, railroad preemption, and school area signals.

DEFINITIONS

Actuation - The operation of any type of detector.

Background Cycle - A term used to identify the cycle length established by a master controller unit or coordination units in coordinated systems.

Conflict Flash - See Emergency Flash.

Controller Assembly - A complete electrical mechanism mounted in a cabinet for controlling the operation of a traffic control signal.

Controller Unit - That part of a controller assembly which performs the basic timing and logic functions.

Coordination - The establishment of a definite timing relationship between adjacent signal installations.

Cycle - See Signal Cycle.

Emergency Flash - Flashing operation which is initiated by the conflict monitor in the signal controller.

Fixed Time Operation - See pretimed operation.

Flasher - A device used to open and close signal circuits at a repetitive rate.

Flashing Operation - Traffic control signal operation in which a flashing yellow or flashing red indication is displayed to approaching traffic.

Full-Actuated Operation - See Traffic-Actuated Operation.

Isolated Intersection - A signalized intersection that is located at least one-half mile from any adjacent signalized intersection.

Major Street - The roadway approach or approaches at an intersection normally carrying the major volume of vehicular traffic. Note: the "major street" may change during the day with changes in the traffic pattern.

Memory Off - A form of detector operation in which an actuation call is dropped by the detector unit after the vehicle leaves the detection zone.

Memory On - A form of detector operation in which an actuation call is maintained or "remembered" by the detector unit even after the vehicle leaves the detection zone.

Minor Street - The roadway approach or approaches at an intersection normally carrying the minor volume of vehicular traffic. Note: the "minor street" may change during the day with changes in the traffic pattern.

Normal Operation - Traffic control signal operation in which steady green, yellow, and red indications are displayed to approaching traffic.

Phase - The right-of-way interval (green) and vehicle change interval (yellow) in a cycle that are assigned to an independent traffic movement or combination of movements.

Preemption - The transfer of normal operation of signals to a special control mode which may be required by railroad trains at crossings, emergency vehicles, mass transit equipment, or for other special needs.

Pretimed Controller Unit - A controller unit in which cycle length(s), interval duration(s), and interval sequence(s) are predetermined.

Pretimed Operation - A type of operation in which cycle length(s), interval duration(s), and interval sequences(s) are predetermined.

Red Clearance Interval - An interval following the yellow clearance interval in which a red indication is displayed to all traffic movements.

Regular Operation - See normal operation.

Right-of-Way Interval - The portion of a signal cycle in which a green indication is displayed to one or more movements.

Semi-Actuated Controller Unit - A type of traffic-actuated controller unit in which detectors are provided for traffic actuation on one or more but not all approaches to an intersection.

Semi-Actuated Operation - A type of operation of a traffic-actuated controller unit in which one or more phases are operated on a non-actuated basis.

Signal Cycle - The total time required to complete one sequence of signal phases at a signalized intersection with pretimed operation or a sequence of those phases with traffic demand at a signalized intersection with traffic-actuated operation.

Signal Face - That part of a signal head provided for controlling traffic in a single direction.

Signal Head - An assembly containing one or more signal faces that may be designated as one-way, two-way, etc.

Signal Housing - That part of a signal section that protects the light source and other required components.

Signal Indications - The illumination of a signal lens or equivalent device or a combination of several lenses or devices at the same time.

Signal Installation - The traffic signal equipment, signal head supports, and electrical circuitry necessary to control vehicular and/or pedestrian traffic at an intersection.

Signal Lens - That part of a signal section through which light from the light source and/or reflectors passes and, in doing so, is directed into a prescribed pattern, is filtered to a prescribed color, and, where necessary, is provided with a pre-described symbol or message.

Signal Section - The assembly of a housing, lens, and light source with necessary components and supporting hardware to be used for providing one signal indication.

Signal System - Two or more traffic control signals operating in coordination.

Signal Visor - That part of a signal section which directs the signal indication specifically to approaching traffic and reduces the effect of direct external light entering the lens.

Soft Recall - A type of traffic-actuated operation in which a green indication is continuously displayed to the major street until an actuation is detected on the minor street.

Track Clearance - An initial interval of the railroad preemption special control mode during which that traffic which is stopped on the railroad tracks when preemption is initiated is given a signal indication(s) allowing that traffic to clear the tracks before the train reaches the crossing.

Traffic Control Signal - Any power-operated traffic control device (except a sign, barricade warning light, or steady burning electrical lamp) by which traffic is warned or is directed to take some specific action.

Traffic-Actuated Controller Unit - A type of controller unit for supervising the operation of a traffic control signal in accordance with the varying demands of traffic, as registered with the controller unit by detectors.

Traffic-Actuated Operation - A type of controller unit operation in which green interval durations are varied in accordance with the varying demands of traffic, as registered with the controller unit by detectors.

Volume Ratio - The ratio of major street to minor street traffic volume. The volume ratio can be calculated for a given hour, portion of a day, or for a 24-hour period.

Warrant - A threshold condition which, when found to be met as part of an engineering study, shall result in analysis of other traffic conditions or factors in determining if a traffic control device or other improvement is justified.

Yellow Clearance Interval - The first interval following the green right-of-way interval in which the signal indication for that phase is yellow.

CHAPTER 9

REFERENCES

1. *Texas Manual on Uniform Traffic Control Devices*. Texas State Department of Highways and Public Transportation, Austin, Texas. 1980, revised to 1988.
2. *Manual on Uniform Traffic Control Devices,* American Association of State Highway Officials, National Conference on Street and Highway Safety, Washington, D.C., 1935.
3. Guido Radelat. *Accident Experience as Related to Regular and Flashing Operation of Traffic Signals, A Staff Report*. District of Columbia Department of Highways and Traffic, Washington, D.C., June 1966.
4. G.B. Gurnett. L.A. County Study of 24-Hour Operation of Pretimed Signals. *Traffic Engineering*. Institute of Traffic Engineers, Washington, D.C., May 1972.
5. Joseph A. Marson. *A Comparison of Accident Experience at Intersections with Flashing and Regular Traffic Signal Control During Low-Volume Time Periods.* M.S. Thesis, Department of Civil Engineering, Michigan State University, 1976.
6. Berry Benioff, Cynthia Carson, and Fredrick C. Dock. *A Study of Clearance Intervals, Flashing Operation, and Left-turn Phasing at Traffic Signals: Volume 3 Flashing Operation.* FHWA-RD-78-48. U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., May 1980.
7. J.C. Barbaresso. Flashing Signal Accident Evaluation. *Transportation Research Record 956.* Transportation Research Record, Washington, D.C., 1984.
8. J.C. Barbaresso. Relative Accident Impacts of Traffic Control Strategies During Low-Volume Nighttime Periods. *ITE Journal,* Institute of Transportation Engineers, Washington, D.C., August 1987.
9. J.C. Barbaresso. A Case Study of the Accident Impacts of Flashing Signal Operations Along Roadways. *ITE Journal,* Institute of Transportation Engineers, Washington, D.C., July 1987.
10. M.F. Akbar and F.D. Layton. Accident Experience of Flashing Traffic Signal Operation in Portland, Oregon. *Transportation Research Record 1069.* Transportation Research Record, Washington, D.C., 1986.
11. Harvey Quan. San Francisco's Experience with Flashing Signals. *WesternITE*, August-September 1975.

12. J.W. Hall. Fuel Saving Potential of Low-Cost Traffic Engineering Improvements. *Transportation Research Record 816.* Transportation Research Record, Washington, D.C. 1981.
13. K.N. Womack, H.G. Hawkins, J.M. Mounce. *Motorist Comprehension of Traffic Control Devices: Statewide Survey Results*. Research Report 1261-2. Texas Transportation Institute, Texas A&M University, College Station, Texas, February 1993.
14. E.B. Lieberman, G. F. King, and R. B. Goldblatt. *Traffic Signal Warrants: Volumes I and II. Final Report, Project 3-20.* National Cooperative Highway Research Program, Washington, D.C., December 1976.
15. P.S. Parsonson and D.J. Walker. *Issues in Flashing Operation for Malfunctioning Traffic Signals.* TRB Preprint 920849. Transportation Research Board, Washington, D.C., January 1992.
16. American Association of State Highway and Transportation Officials. *A Policy on Geometric Design of Highways and Streets*. Washington, D.C., 1990.
17. Fred L. Orcutt. *The Traffic Signal Book.* Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1993.
18. *Manual on Uniform Traffic Control Devices,* Bureau of Public Roads, Washington, D.C., 1961.
19. J.R. Black. Municipality Policy Survey on the Use of Night Flash. *TexITE Newsletter.* October 1991.
20. *Manual on Uniform Traffic Control Devices,* Federal Highway Administration, Washington, D.C., 1988.
21. *Manual on Uniform Traffic Control Devices,* Public Roads Administration, Washington, D.C., 1948.
22. R.L. Bleyl. Simulation of Traffic Flow to Compare Regular and Flashing Signal Operation. *Proceedings, 34th Annual Meeting*, Institute of Traffic Engineers, Washington, D.C., November 1964.
23. *Texas Manual on Uniform Traffic Control Devices.* Texas Highway Department, Austin, Texas. 1954.
24. *Texas Manual on Uniform Traffic Control Devices.* Texas Highway Department, Austin, Texas. 1967.
25. *Texas Manual on Uniform Traffic Control Devices.* Texas Highway Department, Austin, Texas. 1973.

26. *Manual on Uniform Traffic Control Devices,* Federal Highway Administration, Washington, D.C., 1971.

27. *Manual on Uniform Traffic Control Devices,* Federal Highway Administration, Washington, D.C., 1978.

28. *Traffic Control Devices Handbook.* Federal Highway Administration, Washington, D.C. 1983.

29. *Traffic Signal Applications Manual.* Department of Transportation, City of Arlington, Texas, February 1988.

30. *Traffic Engineering and Operations Manual.* Commonwealth of Pennsylvania Department of Transportation, Harrisburg, Pennsylvania, April 1987.

31. *Special Report 209, Highway Capacity Manual.* Transportation Research Board, National Research Council, Washington, D.C., 1985.

32. R. Wilshire, R. Black, R. Grochoske, and J. Higinbotham. *Traffic Control Systems Handbook; Revised Edition - 1985.* FHWA-IP-85-11, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., April 1985.

33. *TR Circular 373, Interim Materials on Unsignalized Intersection Capacity.* Transportation Research Board, National Research Council, Washington, D.C., July 1991.

34. W.N. Volk. Effect of Type of Controls on Intersection Delay. *Proceedings*, Highway Research Board, Volume 35, 1956.

35. Wilbur Smith and Associates. *Traffic Signal Warrant for Heavy Traffic Volumes Occurring During Short Periods of Time (A Tentative Peak Hour Delay Warrant).* Report for the West Virginia Department of Highways, April 1975.

36. R.B. Machemaehl and M. Acampora. *Texas Model Validation for Left-Turn Phasing Alternatives.* Research Report 1906-1, Center for Transportation Research, University of Texas, Austin, Texas, March 1991.

37. C.E. Lee, R.B. Machemaehl, T.W. Rioux, and R.F. Inman. *TEXAS Model Version 3.0 Documentation (Diamond Interchanges) with Supplements for Version 3.10 and Version 3.11.* Research Report 443-1F, Center for Transportation Research, University of Texas, Austin, Texas, March 1989.

38. A.E. Radwan, F. Naguib, and J. Upchurch. Assessment of the Traffic Experimental and Analysis Simulation Computer Model Using Field Data. *Transportation Research Record 1320.* Transportation Research Board, National Research Council, Washington, D.C., 1991.

39. F.V. Webster. *Traffic Signal Settings*. Road Research Technical Paper No. 39, Her Majesty's Stationery Office, London, England, 1958.

40. C.J. Messer and M.S. Chang. *Guidelines for Installing Traffic Signals at Diamond Interchanges*. Research Report 344-1, Texas Transportation Institute, Texas A&M University, College Station, Texas, November 1984.

41. *Highway Safety Evaluation: Procedural Guide*. FHWA-TS-81-219. U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., November 1981.

42. Olga J. Pendleton. *A Systemwide Methodology for Evaluating Highway Safety Studies*. FHWA-RD-92-049. U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., October 1992.

43. Martin T. Pietrucha, Kenneth S. Opiela, Richard L. Knoblauch, Kristy L. Crigler. *Motorist Compliance with Standard Traffic Control Devices*, FHWA-RD-89-103. U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., April 1989.

44. P.C. Box and W.A. Alroth. Warrants for Traffic Control Signals, Part I. *Traffic Engineering*. Institute of Traffic Engineers, Washington, D.C., November 1967.

45. JHK & Associates and Wagner-McGee Associates. *User Guide for Removal of Not Needed Traffic Signals*, FHWA-IP-86-215. U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., November 1980.

46. J.L. Kay, L.G. Neudorf, and F.A. Wagner. *Criteria for Removing Traffic Signals*. U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., September 1980.

47. B.H. Tustin, H. Richards, H. McGee, R. Patterson. *Railroad-Highway Grade Crossing Handbook, 2nd Edition*. FHWA-TS-86-215. U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., September 1986.

APPENDIX A
INSTRUMENT FOR TEXAS PRACTICES SURVEY

The following pages contain the survey instrument used to identify practices related to flashing operation of traffic signals. The survey instrument was distributed to TxDOT districts and local transportation agencies. The agencies listed in Tables A-1 and A-2 responded to the survey.

Table A-1. TxDOT Districts Responding to Survey of Texas Practices

No.	City	No.	City	No.	City
1	Paris	9	Waco	17	Bryan
2	Fort Worth	10	Tyler	18	Dallas
3	Wichita Falls	11	Lufkin	19	Atlanta
4	Amarillo	12	Houston	20	Beaumont
5	Lubbock	13	Yoakum	21	Pharr
6	Odessa	14	Austin	23	Brownwood
7	San Angelo	15	San Antonio	24	El Paso
8	Abilene	16	Corpus Christi	25	Childress

Table A-2. Local Agencies Responding to Survey of Texas Practices

Cities			Counties
Abilene Amarillo Arlington Austin Baytown Beaumont Brownwood Carrollton	Dallas El Paso Fort Worth Garland Houston Irving Laredo	Lubbock Midland Pasadena Richardson San Antonio Tyler Waco	Dallas County

FLASHING TRAFFIC SIGNAL SURVEY

Texas Transportation Institute / Texas Department of Transportation

Name: ____________________
Agency: ____________________
Address: ____________________
Phone: ____________________

1. Are there any signalized intersections within your jurisdiction which use flashing operation on a regular (or normal) basis?
   ☐ Yes ☐ No
   Comments:

2. Under what conditions does your district or agency place traffic signals in flashing operation? (check all that apply).
   ☐ Do not place signals in flashing operation.
   ☐ Emergency (due to some type of signal failure)
   ☐ Railroad preemption
   ☐ Early morning hours
   ☐ Low-volume periods (other than early morning hours)
   ☐ School areas
   ☐ Signal installation and/or removal
   ☐ Other (please describe)

3. Please indicate any factors which are addressed in your district or agency guidelines for flashing operation, if you have such guidelines. (check all that apply)
   ☐ No guidelines for flashing operation
   ☐ Traffic volume
   ☐ Accidents
   ☐ Time of day
   ☐ Day of week
   ☐ Posted speeds
   ☐ Relation to other intersections
   ☐ Geometrics
   ☐ Other (please describe)

4. Would guidelines for flashing signal operation be useful to your agency?
   ☐ Yes ☐ No ☐ Maybe

5. If you use normal flashing operation, can TTI study flashing operation at one or more of these intersections?
   ☐ Yes ☐ No ☐ Maybe
   Comments:

6. Do you use flashing operation with actuated controllers?
   ☐ Yes ☐ No ☐ Maybe
   Comments:

7. Have you ever performed an analysis of the effectiveness of flashing operation?
   - ☐ Yes (Please enclose a copy of the report)
   - ☐ No

8. Would you be willing to implement flashing operation within your jurisdiction on an experimental basis using the preliminary guidelines developed in this research?

   ☐ Yes ☐ No ☐ Maybe

   Comments:

9. On what basis do you select the color indications (yellow/red or red/red) for flashing operations?

10. Please make any suggestions about aspects of flashing signal operation which you think should be studied. (use back of sheet or additional paper if necessary)

Please return to: (return label enclosed for convenience)
H. Gene Hawkins, Jr., P.E.
Texas Transportation Institute
Texas A&M University System
College Station, Texas 77843-3135

Phone: (409) 845-1535

APPENDIX B
RESPONSES FOR TEXAS PRACTICES SURVEY

Note: The number of responses is shown for each answer, followed by the response percentage in parenthesis.

1. Are there any signalized intersections within your jurisdiction which use flashing operation on a regular (or normal) basis?

	TxDOT	Local	Total
YES	16 (66.7%)	17 (73.9%)	33 (70.2 %)
NO	8 (33.3%)	6 (26.1%)	14 (29.8 %)

2. Under what conditions does your district or agency place traffic signals in flashing operation? (check all that apply).

	TxDOT	Local	Total
Do not place signals in flashing operation.	1 (4.2%)	0 (0.0%)	1 (2.1%)
Emergency (due to signal failure)	23 (95.8%)	22 (95.7%)	45 (95.7%)
Railroad preemption	17 (70.8%)	9 (39.1%)	26 (55.3%)
Early morning hours	14 (58.3%)	17 (73.9%)	31 (66.0%)
Low-volume (other than early morning)	3 (12.5%)	7 (30.4%)	10 (21.3%)
School areas	2 (8.3%)	6 (26.1%)	8 (17.0%)
Signal installation and/or removal	18 (75.0%)	14 (60.9%)	32 (68.1%)
Other (please describe)	3 (12.5%)	6 (26.1%)	9 (19.1%)
Construction/maintenance areas	0 (0.0%)	2 (8.7%)	2 (4.3%)
Equipment testing	1 (4.2%)	0 (0.0%)	1 (2.1%)
Inclement weather	1 (4.2%)	1 (4.3%)	2 (4.3%)
Shopping centers/fire station entrances	1 (4.2%)	2 (8.7%)	3 (6.4%)
Special events	0 (0.0%)	1 (4.3%)	1 (2.1%)

3. Please indicate any factors which are addressed in your district or agency guidelines for flashing operation, if you have such guidelines. (check all that apply)

	TxDOT	Local	Total
No guidelines	11 (45.8%)	11 (45.8%)	22 (46.8%)
Traffic volume	10 (43.5%)	13 (56.5%)	23 (48.9%)
Accidents	4 (16.7%)	7 (30.4%)	11 (23.4%)
Time of day	8 (33.3%)	11 (47.8%)	19 (40.4%)
Day of week	2 (8.3%)	6 (26.1%)	8 (17.0%)
Posted speeds	1 (4.2%)	4 (17.4%)	5 (10.6%)
Relation to other intersections	3 (12.5%)	4 (17.4%)	7 (14.9%)
Geometrics	1 (4.2%)	6 (26.1%)	7 (14.9%)
Other (please describe)	6 (25.0%)	3 (13.0%)	9 (19.1%)

Local agency input
Snow or ice on road
Fixed time signal on low-volume, early-morning operation
Some actuated coordinated systems in early morning
As listed in the Texas MUTCD
Guidelines are not formal, each intersection considered individually
Type of signal operation

4. Would guidelines for flashing signal operation be useful to your agency?

	TxDOT *	Local	Total
YES	11 (45.8%)	16 (69.6%)	27 (57.4%)
NO	3 (12.5%)	1 (4.3%)	4 (8.5%)
MAYBE	9 (37.5%)	6 (26.1%)	15 (31.9%)

*1 district did not respond to this question

5. If you use normal flashing operation, can TTI study flashing operation at one or more of these intersections?

	TxDOT	Local	Total
YES	12 (50.0%)	17 (73.4%)	29 (61.7%)
NO	3 (12.5%)	0 (0.0%)	3 (6.4%)
MAYBE	3 (12.5%)	1 (4.3%)	4 (8.5%)
NOT APPLICABLE	6 (25.0%)	5 (21.7%)	11 (23.4%)

6. Do you use flashing operation with actuated controllers?

	TxDOT	Local*	Total
YES	9 (37.5%)	13 (56.5%)	22 (46.8%)
NO	11 (45.8%)	7 (30.4%)	18 (38.3%)
MAYBE	4 (16.7%)	1 (4.3%)	5 (10.6%)

*2 cities did not respond to this question

Comments:

Only for railroads crossing, emergency, and/or maintenance needs.

For railroad preemption, maintenance and equipment performance testing.

Only during conflicts; installation; repair; and coordinated, low-volume, early-morning hours.

Bridges-intersections with bad loops.

Limited to emergency flash and railroad preemption.

One local agency has mostly semi-actuated controllers

Motorists perception of delay, system rest in all red flash.

7. Have you ever performed an analysis of the effectiveness of flashing operation?

	TxDOT	Local	Total
YES	0 (0.0%)	4 (17.4%)	4 (8.5%)
NO	24 (100.0%)	19 (82.6%)	43 (91.5%)

8. Would you be willing to implement flashing operation within your jurisdiction on an experimental basis using the preliminary guidelines developed in this research?

	TxDOT	Local	Total
YES	8 (33.3%)	9 (39.1%)	17 (36.2%)
NO	3 (12.5%)	1 (4.3%)	4 (8.8%)
MAYBE	13 (54.2%)	13 (56.5%)	26 (57.8%)

9. On what basis do you select the color indications (yellow/red or red/red) for flashing operations?

   Common responses:

   On equal volume arterial and cross street approaches, red/red is used. When proportional difference become a factor, yellow/red is used.

   Some agencies specify either red/red or yellow/red on all signals making right-of-way less confusing.

   Traffic signal location and traffic volumes.

10. Please make any suggestions about aspects of flashing signal operation which you think should be studied. (use back of sheet or additional paper if necessary)

    Common responses:

    Color indication for left-turn lanes.

    Motorist understanding of flashing right-of-way.

    Flashing sequence for a diamond interchange that does not meet signal warrants.

    Value of flashing an actuated signal.

    Liability.

    Placement of signals near a school that does not meet other signal warrants.

    Conflict flash vs. maintenance flash and off-hours flash.

APPENDIX C
INSTRUMENT FOR WINTER WEATHER SURVEY

The following pages contain the survey instrument used to identify practices related to flashing operation of traffic signals during periods of winter weather. The survey instrument was distributed to state and local transportation agencies located in cold-weather climates. The agencies listed in Table C-1 responded to the survey.

Table C-1. Agencies Responding to Winter Weather Survey

State Agencies	County Agencies	City Agencies
Colorado DOT	Arlington County, Virginia	Aurora, Colorado
Delaware DOT	Dakota County, Minnesota	Beloit, Wisconsin
Kentucky Dept. of Highways	Kalamazoo County, Michigan	Boston, Massachusetts
Michigan DOT	Montgomery County, Maryland	Columbus, Ohio
Minnesota DOT - Duluth District	Nassau County, New York	Flint, Michigan
New Hampshire DOT	Waukesha County, Wisconsin	Grand Island, Nebraska
Pennsylvania DOT		Iowa City, Iowa
West Virginia DOT		Lansing, Michigan
Wyoming DOT		Milwaukee, Wisconsin
Virginia DOT		Minneapolis, Minnesota

SURVEY ON FLASHING TRAFFIC SIGNAL OPERATION DURING ADVERSE WEATHER CONDITIONS

Texas Transportation Institute / Texas Department of Transportation

Name: ______________________________
Agency: ______________________________
Address: ______________________________
Phone: ______________________________

This survey is being conducted to assess traffic signal operational practices during adverse weather conditions. Of primary interest is signal operation when snow or ice create potentially hazardous operating conditions at intersections. For the purposes of this survey, **flashing signal operation** refers to the use of flashing red and/or flashing yellow indications at an intersection, as opposed to normal (green-yellow-red) operation. **Yellow/red flashing operation** refers to the situation in which one roadway is given a flashing yellow indication and the intersecting roadway is given a flashing red indication. **Red/red flashing operation** refers to the situation in which both roadways are given a flashing red indication at the intersection.

1. Does your agency have a policy on traffic signal operations during adverse weather conditions, such as when snow or ice are present on the roadway?

   ☐ Yes ☐ No

2. If your agency does have a policy, is it a written policy?

   ☐ Yes ☐ No

3. If your agency does have a written policy, would it possible for TTI to obtain a copy?

   ☐ Yes ☐ No

4. What actions, if any, does your agency recommend or mandate for traffic signal operations during snow and/or icy weather?

5. Does your agency ever place traffic signals in flashing mode when snow and/or ice are present on the roadway?

   ☐ Yes ☐ No

6. If signals are placed in flashing mode when snow and/or ice are present, which of the following apply? Please specify color combination (e.g. - yellow/red or red/red).

   ☐ Program Flash
   Color combination: ______________________________

   ☐ Emergency Flash
   Color Combination: ______________________________

   ☐ Other
   Please specify: ______________________________

7. If signals are placed in flashing mode when snow and/or ice are present, has your agency encountered any problems or difficulties associated with this mode of operation?

   ☐ Yes ☐ No

   If yes, please briefly list or describe these problems.

8. If signals are <u>not</u> placed in flashing mode when snow and/or ice are present, was this type of operation ever considered as an option?

   ☐ Yes ☐ No

   If yes, on what basis was the decision to reject flashing operation during these adverse weather conditions made?

9. Please add any comments or suggestions that you may have regarding signal operation during adverse weather conditions, or about flashing signal operation in general. (Use the back of this page or attach additional pages if necessary.)

Please return to: (a return label is enclosed for your convenience)

Rick Bartoskewitz
Texas Transportation Institute
Texas A&M University System
College Station, Texas 77843-3135
Phone: (409) 845-9929

Thank you for your participation.

APPENDIX D
RESPONSES FOR WINTER WEATHER SURVEY

Note: The number of responses is shown for each answer, followed by the response percentage in parenthesis.

1. Does your agency have a policy on traffic signal operations during adverse weather conditions, such as when snow or ice are present on the roadway?

   ☐ Yes *4 (14.3%)* ☐ No *24 (85.7%)*

2. If your agency does have a policy, is it a written policy?

   ☐ Yes *0 (0.0%)* ☐ No *4 (100.0%)*

3. If your agency does have a written policy, would it possible for TTI to obtain a copy?

   ☐ Yes *not applicable* ☐ No *not applicable*

4. What actions, if any, does your agency recommend or mandate for traffic signal operations during snow and/or icy weather?

   No action(s) was specified: *15 (53.6%)*
   Action(s) was specified: *13 (46.4%)*

5. Does your agency ever place traffic signals in flashing mode when snow and/or ice are present on the roadway?

   ☐ Yes *5 (17.9%)* ☐ No *23 (82.1%)*

6. If signals are placed in flashing mode when snow and/or ice are present, which of the following apply? Please specify color combination (e.g. - yellow/red or red/red).

   ☐ Program Flash *2 (40.0%)*
   Color combination: *yellow/red: 2 (100.0%)*

   ☐ Emergency Flash *3 (60.0%)*
   Color Combination: *yellow/red: 2 (66.7%) 1 (33.3%)*

   ☐ Other *0 (0.0%)*
   Please specify:

7. If signals are placed in flashing mode when snow and/or ice are present, has your agency encountered any problems or difficulties associated with this mode of operation?

   ☐ Yes *2 (33.3%)* ☐ No *4 (66.7%)*

   If yes, please briefly list or describe these problems.

8. If signals are <u>not</u> placed in flashing mode when snow and/or ice are present, was this type of operation ever considered as an option?

   ☐ Yes *5 (19.2%)* ☐ No *21 (80.8%)*

   If yes, on what basis was the decision to reject flashing operation during these adverse weather conditions made?

9. Please add any comments or suggestions that you may have regarding signal operation during adverse weather conditions, or about flashing signal operation in general. (Use the back of this page or attach additional pages if necessary.)

   Comment(s) provided: *16 (57.1%)*
   No comment(s) provided: *12 (42.9%)*

APPENDIX E
MUTCD PRINCIPLES FOR FLASHING OPERATION

The principles for flashing signal operation contained in the 1980 edition of the Texas MUTCD (1) (revised through 1988) are repeated below. Only those portions of each section which specifically relate to flashing operation are included.

Section 4B-5 Meaning of Signal Indications

4. Flashing signal indications shall have the following meanings:

(a) Flashing red (stop signal) - When a red lens is illuminated with rapid intermittent flashes, drivers of vehicles shall stop at a clearly marked stop line, but if none, before entering the crosswalk on the near side of the intersection, or if none, at the point nearest the intersecting roadway where the driver has a view of approaching traffic on the intersecting roadway before entering the intersection, and the right to proceed shall be subject to the rules applicable after making a stop at a STOP sign.

(b) Flashing yellow (caution signal) - When a yellow lens is illuminated with rapid intermittent flashes, drivers of vehicles may proceed through the intersection or past such signal only with caution.

Section 4B-6 Application of Signal Indications

7. When a traffic control signal is put on flashing operation, normally a yellow indication should be used for the major street and a red indication for the other approaches. Yellow indications shall not be used for all approaches. The following applications shall apply whenever signals are placed in flashing operation:

(a) A CIRCULAR YELLOW indication shall be flashed instead of any YELLOW ARROW indication which may be included in that signal face.

(b) No CIRCULAR GREEN or GREEN ARROW indication or flashing yellow indication shall be terminated and immediately followed by a steady red or flashing red indication without the display of the steady yellow change indication; however, transition may be made directly from a CIRCULAR GREEN or GREEN ARROW indication to a flashing yellow indication.

(c) All signal faces on an approach shall flash the same color of circular indication, except that left turn signal indications may be flashed CIRCULAR RED when adequately shielded or positioned so that through traffic on the approach will not be exposed to substantial visual conflict from the left turn signal indications. The flashing yellow signal indication for through traffic does not have to be shielded or positioned to prevent visual conflict for drivers in the left turn lane.

Section 4B-10 Illumination of Lenses

When 12-inch signals with 150 watt lamps are placed on flashing for nighttime operation and the flashing yellow indication is so bright as to cause excessive glare, an automatic dimming device should be used to reduce the brilliance of the flashing 12-inch yellow.

Section 4B-18 Flashing Operation of Traffic Control Signals

All traffic signal installations shall be provided with an electrical flashing mechanism supplementary to the signal timer. A manual switch, or where appropriate, automatic means, shall be provided to actuate the flashing mechanism. The signal timer shall be removable without affecting the flashing operation. The mechanism shall operate in a manner similar to that of an Intersection Control Beacon (sec. 4E-3) to provide intermittent illumination of selected signal lenses.

The illuminating element in a flashing signal shall be flashed continuously at a rate of not less than 50 nor more than 60 times per minute. The illuminated period of each flash shall be not less than half and not more than two-thirds of the total flash cycle.

When traffic control signals are put on flashing operation, the signal indications given to the several streets shall be as specified in section 4B-6(7).

Automatic changes from flashing to stop-and-go operation shall be made at the beginning of the major street green interval, preferably at the beginning of the common major street green interval, (i.e., when a green indication is shown in both directions on the major street). Automatic changes from stop-and-go to flashing operation shall be made at the end of the common major street red interval, (i.e., when a red indication is shown in both directions on the major street).

The change from the flashing to stop-and-go operation, or from stop-and-go to flashing operation by manual switch may be made at any time.

Where there is no common major street green interval, the automatic change from flashing to stop-and-go operation shall be made at the beginning of the green interval for the major traffic movement on the major street. It may be necessary to provide a short, steady all-red interval for the other approaches before changing from flashing yellow or flashing red to green in the major approach.

When for a period of four or more consecutive hours of the late evening and/or early morning periods, any traffic volume drops to 50 percent or less of the stated volume warrants, pretimed traffic control signals should be placed on flashing operation rather than continue normal operation.

Section 4B-19 Continuity of Operation

A traffic signal installation, except as provided below shall be operated as a stop-and-go device or as a flashing device.

When a signal installation is not in operation, such as prior to placing it in service, during seasonal shutdowns, or when it is not desirable to operate the signals, they should be hooded, turned or taken down to clearly indicate that the signal is not in operation.

When a traffic signal is being operated as a flashing device, all signal faces on an approach shall be flashed.

The above provisions do not apply to emergency traffic signals, movable bridge signals or ramp control signals.

When a single-section, continuously illuminated GREEN ARROW lens is used alone to indicate a continuous movement, it may be continuously illuminated when the other signal indications in the signal installation are flashed.

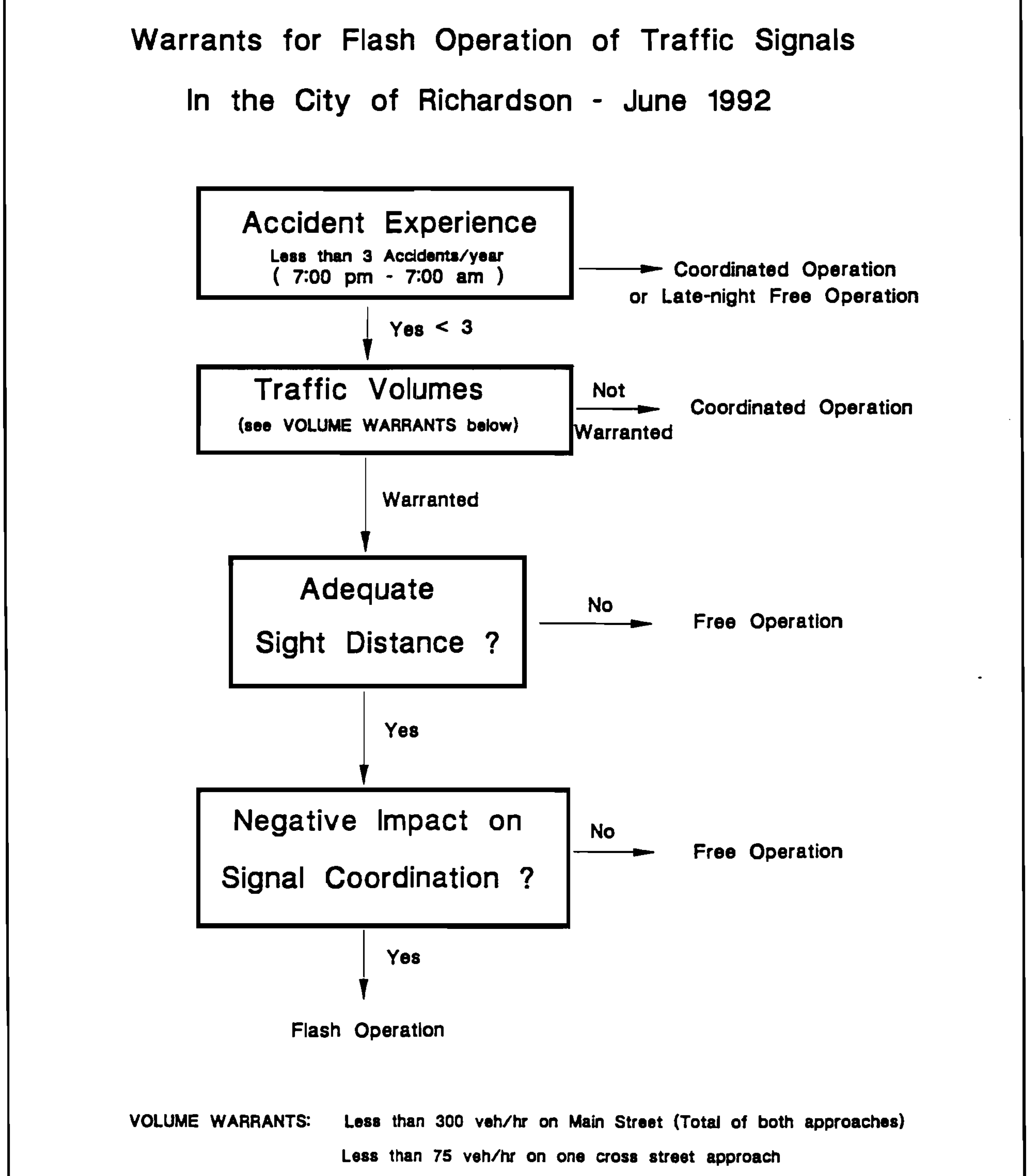
Section 4D-7 Pedestrian Intervals and Phases

4. At intersections equipped with pedestrian signals, the pedestrian signals shall be displayed except when the traffic signal is being operated as a flashing device. At those times, the pedestrian indications shall not be illuminated.

APPENDIX F

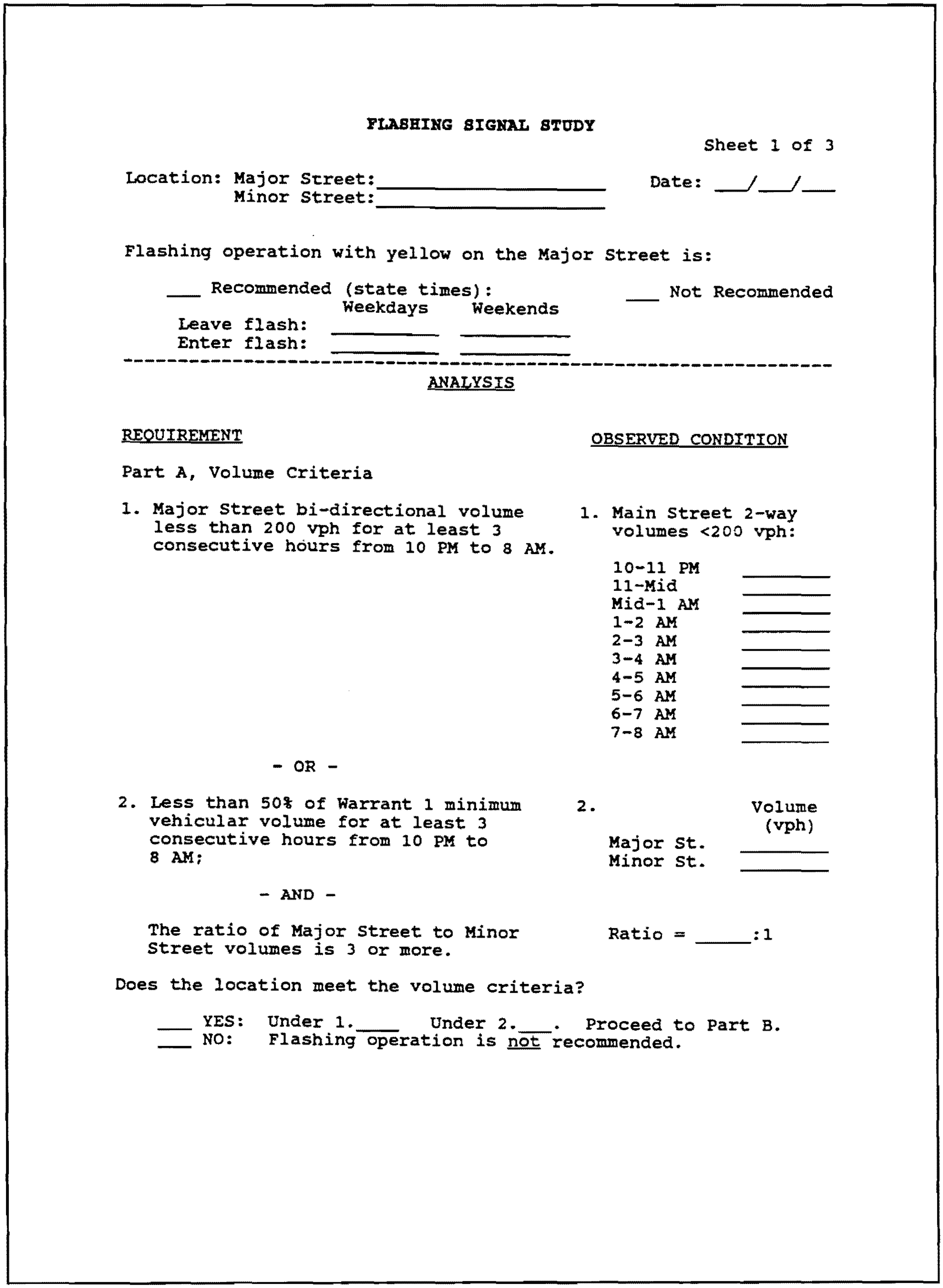
EXISTING GUIDELINES FOR FLASHING OPERATION

The flashing signal guidelines used by the Cities of Arlington and Richardson, Texas are provided in this appendix. Figure F-1 illustrates the policy of the City of Richardson. Figures F-2 and F-3 illustrate the policy of the City of Arlington, described in their signal manual (29).



VOLUME WARRANTS: Less than 300 veh/hr on Main Street (Total of both approaches)
Less than 75 veh/hr on one cross street approach

Figure F-1. City of Richardson Flashing Signal Policy



FLASHING SIGNAL STUDY

Sheet 1 of 3

Location: Major Street:____________________ Date: ___/___/___
Minor Street:____________________

Flashing operation with yellow on the Major Street is:

___ Recommended (state times): ___ Not Recommended

	Weekdays	Weekends
Leave flash:	________	________
Enter flash:	________	________

ANALYSIS

REQUIREMENT	OBSERVED CONDITION
Part A, Volume Criteria	
1. Major Street bi-directional volume less than 200 vph for at least 3 consecutive hours from 10 PM to 8 AM.	1. Main Street 2-way volumes <200 vph:

10-11 PM ________
11-Mid ________
Mid-1 AM ________
1-2 AM ________
2-3 AM ________
3-4 AM ________
4-5 AM ________
5-6 AM ________
6-7 AM ________
7-8 AM ________

- OR -

2. Less than 50% of Warrant 1 minimum vehicular volume for at least 3 consecutive hours from 10 PM to 8 AM;

2.

	Volume (vph)
Major St.	________
Minor St.	________

- AND -

The ratio of Major Street to Minor Street volumes is 3 or more.

Ratio = _____:1

Does the location meet the volume criteria?

___ YES: Under 1.____ Under 2.___. Proceed to Part B.
___ NO: Flashing operation is not recommended.

Figure F-2. City of Arlington Flashing Signal Policy: Part A

Part B, Intersection Characteristics Criteria

1. The location must be within 1000 feet of a regular signalized intersection, and not installed under the accident experience warrant;	1. Location is ____ ft. from a regular signalized intersection and not installed under the accident experience warrant.
- OR -	- OR -
The signal was not installed under the progressive movement or accident experience warrant.	Original Warrant: (Yes or No) Prog. Movement?___ Accident Exp.? ___
2. The Minor Street must have sight distances adequate for 10 MPH in excess of the Major Street's posted speed limits.	2. Actual Minor Street Sight Distances: _____ approach: Right:______ feet Left: ______ feet _____ approach: Right:______ feet Left: ______ feet Major Street speed limits: _____ approach: ______ MPH Needed sight ____' _____ approach: ______ MPH Needed sight ____'

Does the location satisfy both Parts B.1 and B.2?

___ YES. Proceed to Part C.
___ NO. Flashing operation is not recommended.

Part C, Accident History

For before and after accident evaluation, a 24-month accident history shall be established for the period of operation to determine the rates of nighttime right-angle and DWI accidents relative to the same rates over a 24-hour period.	1. Total number of rt. angle accidents in 24 months: _________ 2. Number of nighttime rt. angle accidents in 24 months:_______ 3. Total number of DWI accidents in 24 months: ____________ 4. Number of nighttime DWI accidents in 24 months: ____________

Does the location have accident rates that would be cause for not operating it in the flashing mode?

____ NO. Flashing operation may be considered.
____ YES. Flashing operation is not recommended.

Figure F-3. City of Arlington Flashing Signal Policy: Parts B and C

APPENDIX G
RESULTS OF OPERATIONAL ANALYSIS

This appendix presents the graphical results for the operational analysis of flashing operation at isolated intersections and as part of a signal system.

Isolated Intersection Analysis - Graphical Results

The TEXAS Model was used to simulate signal operations at isolate intersections. The evaluation was based upon using total intersection delay per vehicle as its measure-of-effectiveness. The analysis was performed using a range of traffic volumes from 10 to 500 vehicles per hour (vph) per approach. Because of the stochastic nature of the TEXAS Model, a minimum of five replicate runs were made and were averaged to create a single value to represent total delay. From each simulation output file, total intersection delay per vehicle (seconds of delay per vehicle, spv) was graphed against the major to minor street volume ratio as a function of the major street volume. In other words, the x-axis would represent the major to minor street volume ratio and the y-axis would represent the total delay. The x-axis and y-axis are related by the major street volume.

Figures G-1 through G-4 represent total delay per vehicle for all geometric configurations with red/red flash signal operation. Figures G-5 through G-8 represent total delay per vehicle for all geometric configurations with yellow/red flash signal operation. Figures G-9 through G-12 represent total delay per vehicle for all geometric configurations with pretimed signal operation. And Figures G-13 through G-16 represent total delay per vehicle for all geometric configurations with actuated signal operation.

A comparison was made between each type of signal control for each geometric configuration. The objective was to illustrate the most efficient type of signal control in terms of delay. Figures G-17 through G-19 represent the four types of signal control for the 5×4 geometric configuration. Figures G-20 through G-22 represent the four types of signal control for the 5×2 geometric configuration. Figures G-23 through G-25 represent the four types of signal control for the 4×2 geometric configuration. And Figures G-26 through G-28 represent the four types of signal control for the 2×2 geometric configuration.

Signal System Analysis - Graphical Results

The intersections in a signal system were simulated using the TRAF-NETSIM model. Three signalized intersections, separated by approximately one-half mile spacing, made up the signal system. Because the NETSIM model can not simulate a four-way STOP sign control, the red/red flash operation is not represented here - only the yellow/red flash. The pretimed and actuated signal control has been programmed (or coded) so that the major arterial operates in coordination.

Figures G-29 through G-32 represent the yellow/red flash operation for each of the four geometric configurations. Figures G-33 through G-36 represent the pretimed operation for each of the four geometric configurations. And Figures G-37 through G-40 represent the actuated operation for the four geometric configurations.

As was done for the isolated intersection analysis, a comparison was made between each type of signal control for each geometric configuration. The objective was to illustrate the most efficient type of signal control in terms of delay. Figures G-41 through G-43 represent the three types of signal control for the 5×4 geometric configuration. Figures G-44 through G-46 represent the three types of signal control for the 5×2 geometric configuration. Figures G-47 through G-49 represent the three types of signal control for the 4×2 geometric configuration. And Figures G-50 through G-52 represent the three types of signal control for the 2×2 geometric configuration.

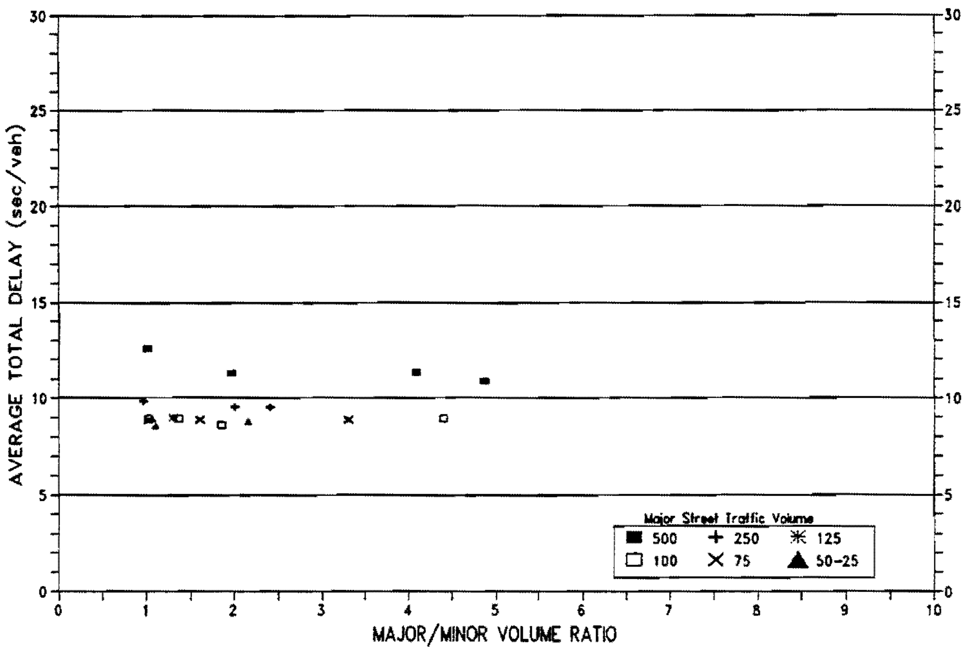


Figure G-1. Red/Red Flash for 5×4 Isolated Intersection

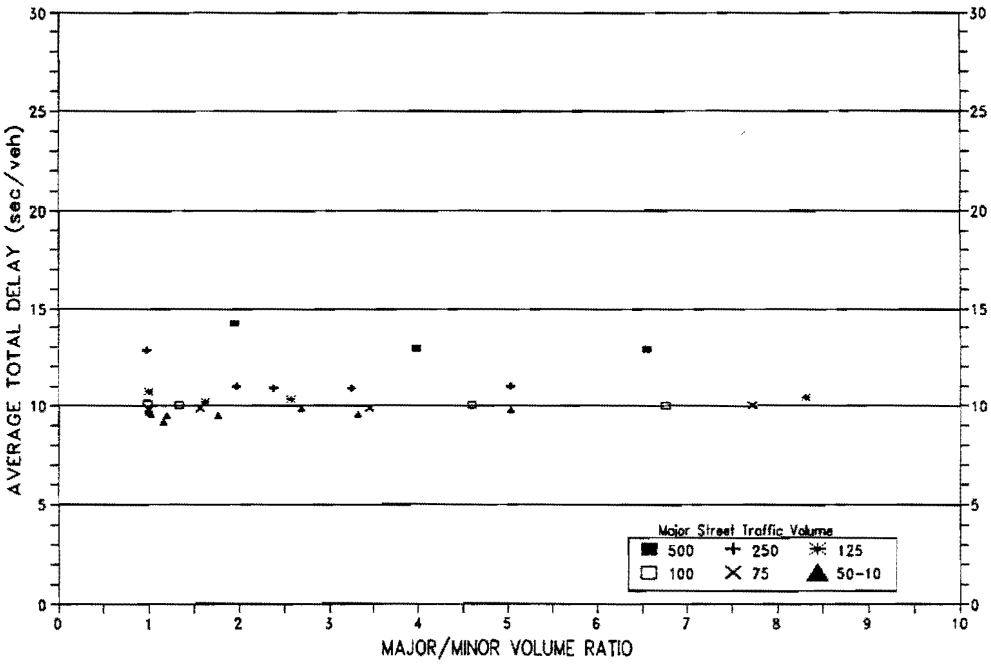


Figure G-2. Red/Red Flash for 5×2 Isolated Intersection

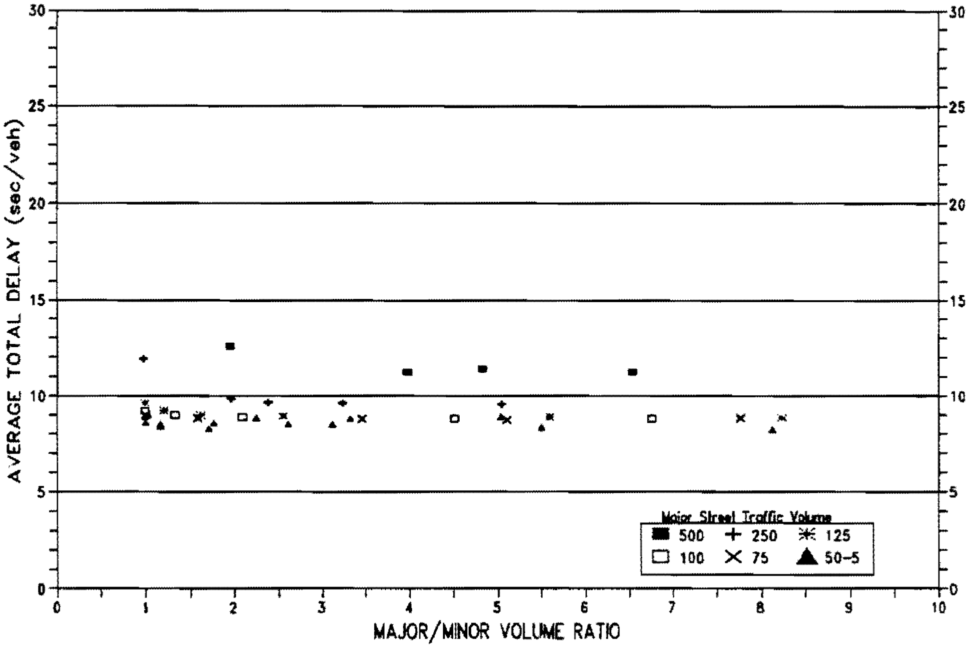


Figure G-3. Red/Red Flash for 4×2 Isolated Intersection

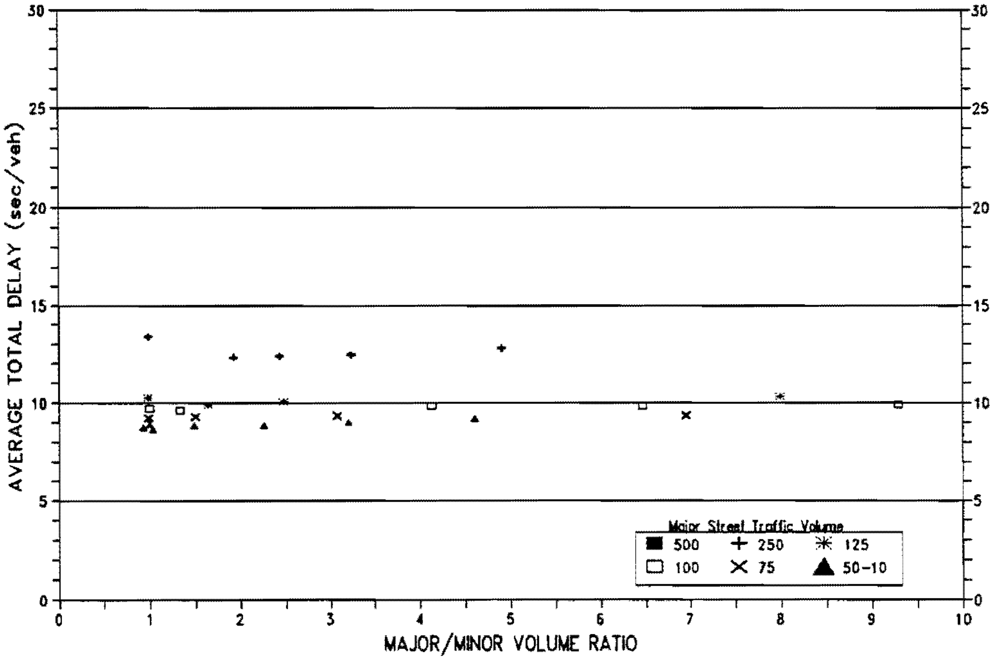


Figure G-4. Red/Red Flash for 2×2 Isolated Intersection

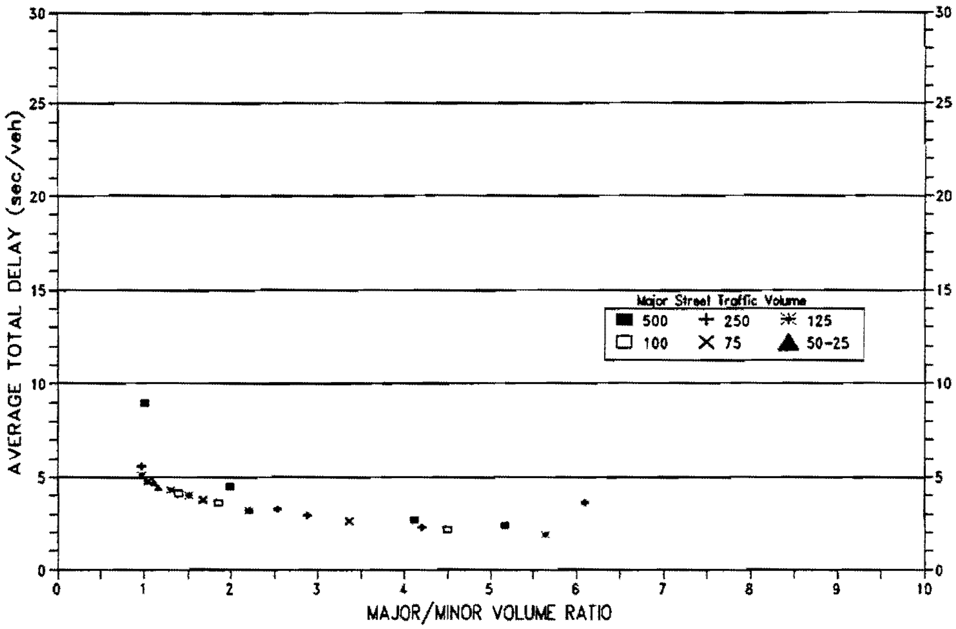


Figure G-5. Yellow/Red Flash for 5×4 Isolated Intersection

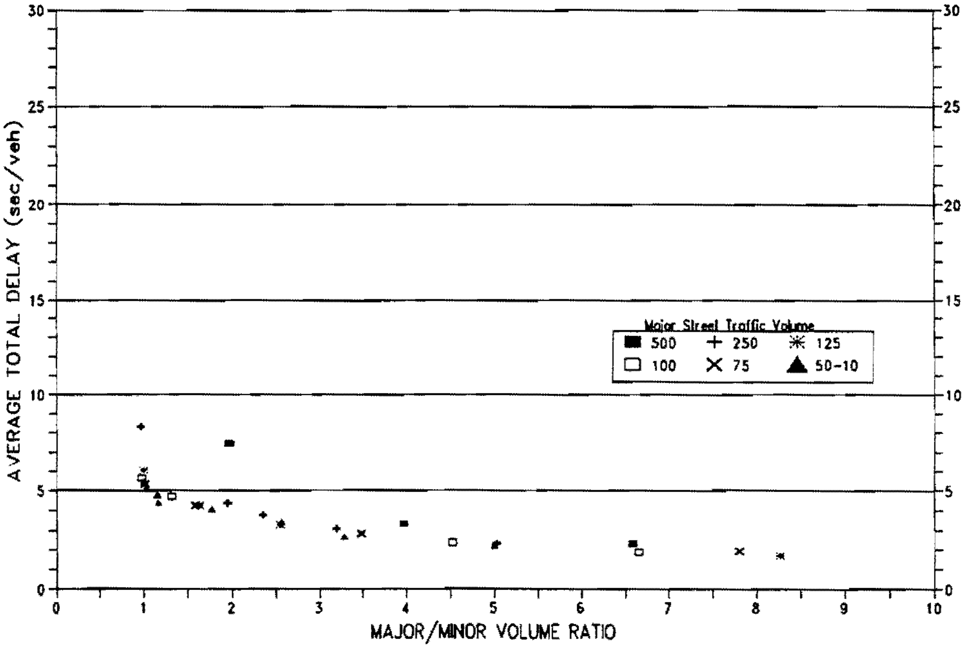


Figure G-6. Yellow/Red Flash for 5×2 Isolated Intersection

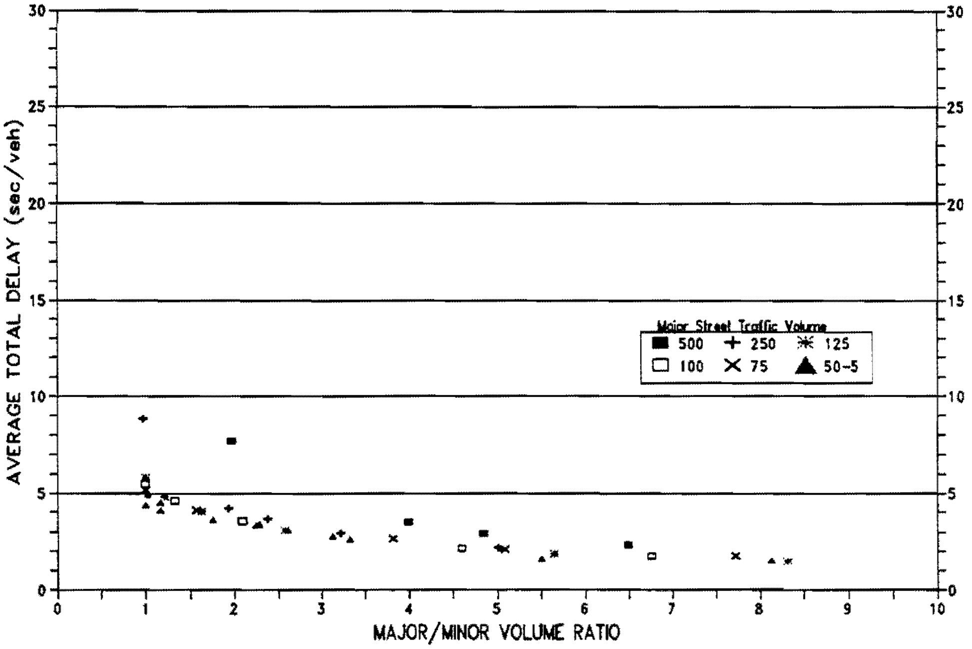


Figure G-7. Yellow/Red Flash for 4×2 Isolated Intersection

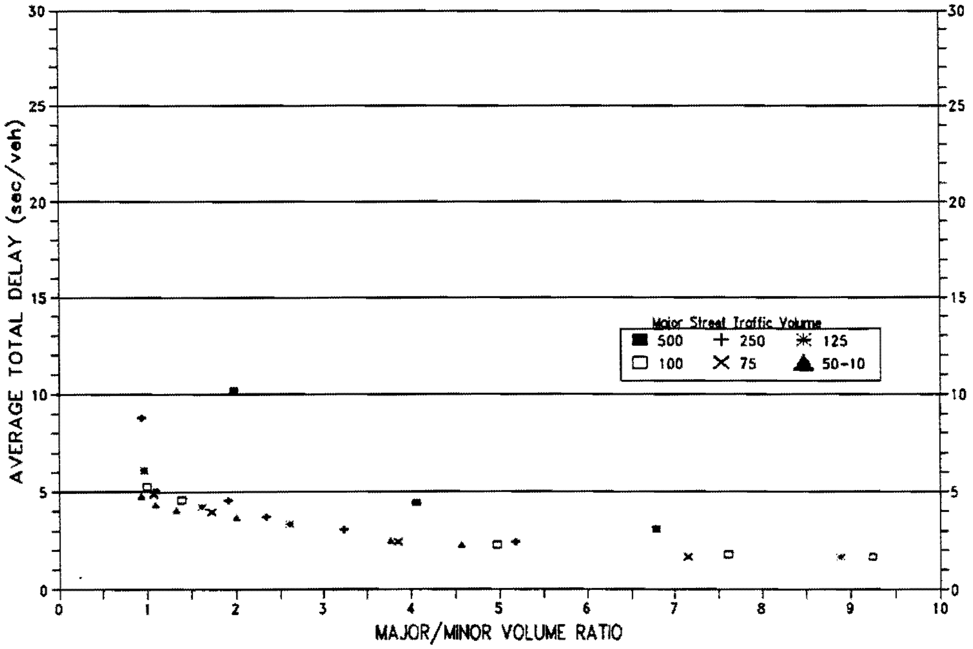


Figure G-8. Yellow/Red Flash for 2×2 Isolated Intersection

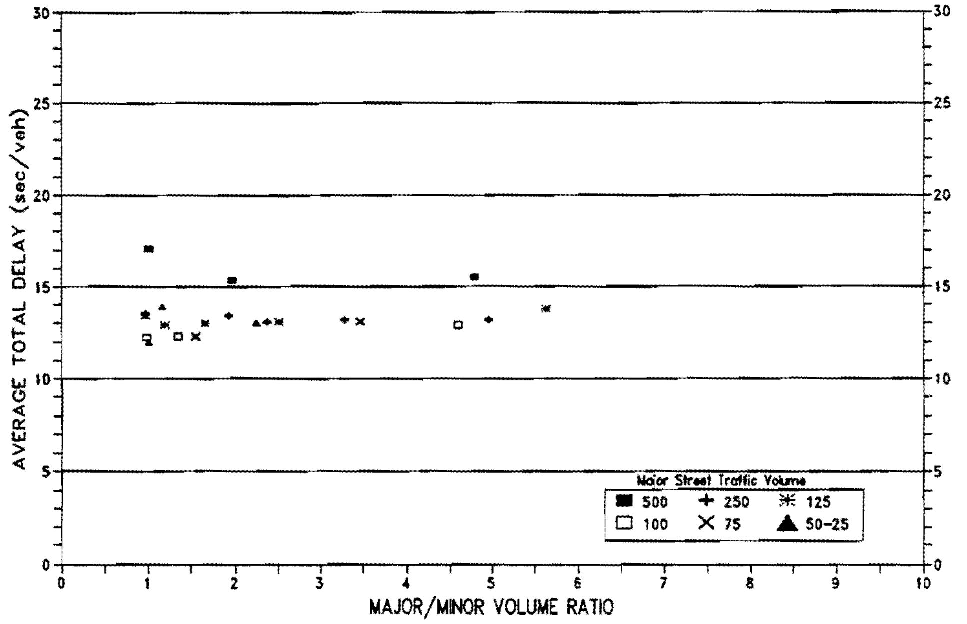


Figure G-9. Pretimed for 5×4 Isolated Intersection

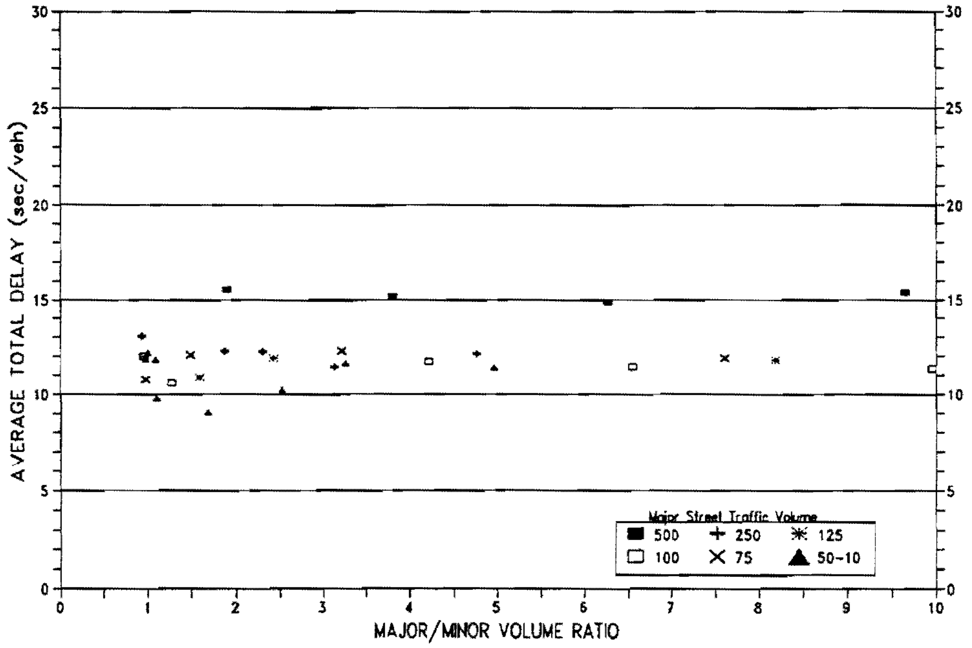


Figure G-10. Pretimed for 5×2 Isolated Intersection

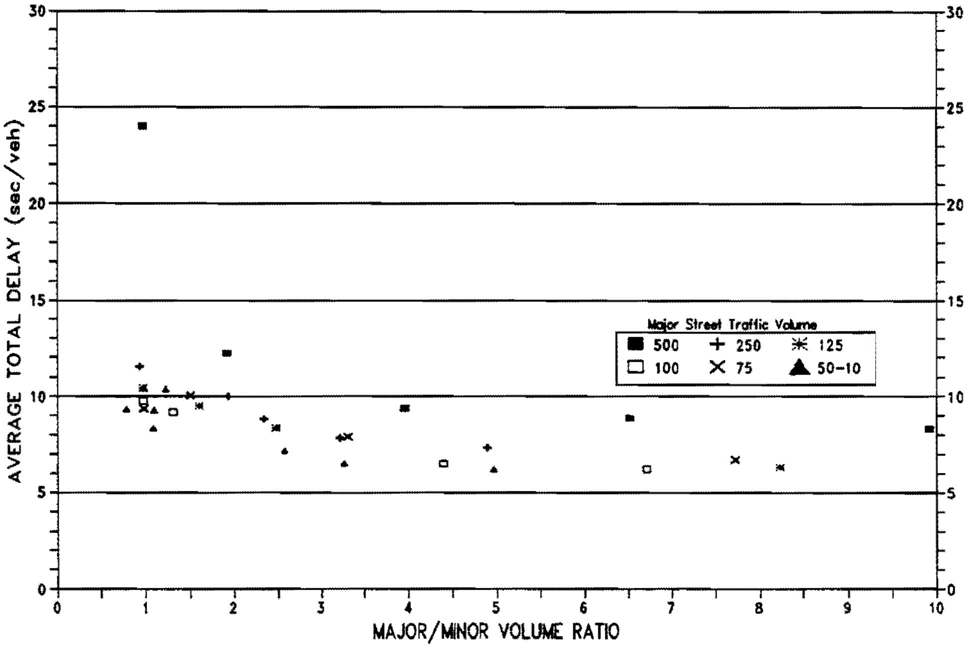


Figure G-11. Pretimed for 4×2 Isolated Intersection

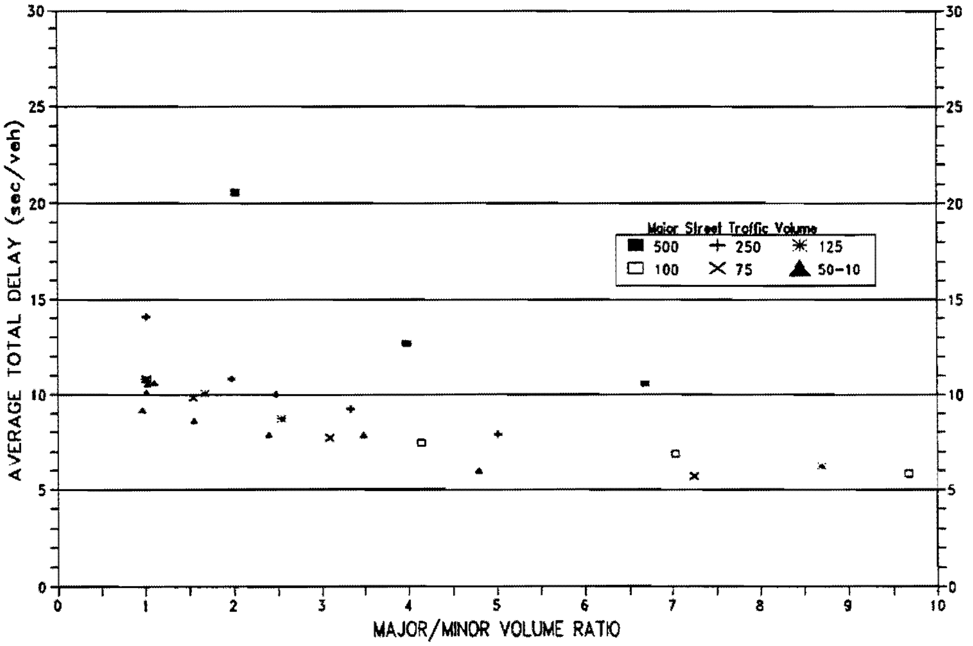


Figure G-12. Pretimed for 2×2 Isolated Intersection

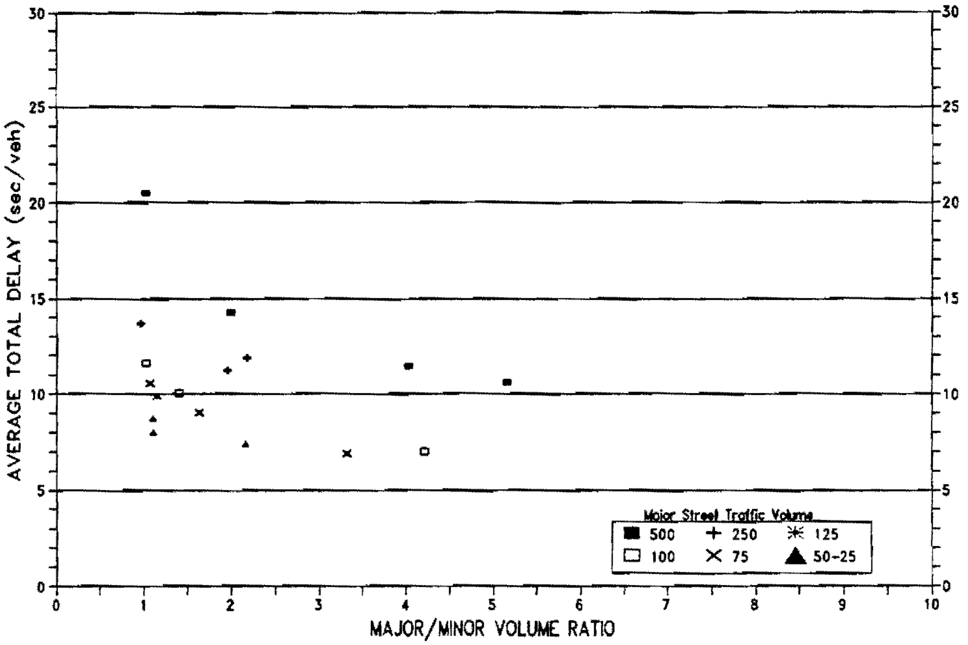


Figure G-13. Actuated for 5×4 Isolated Intersection

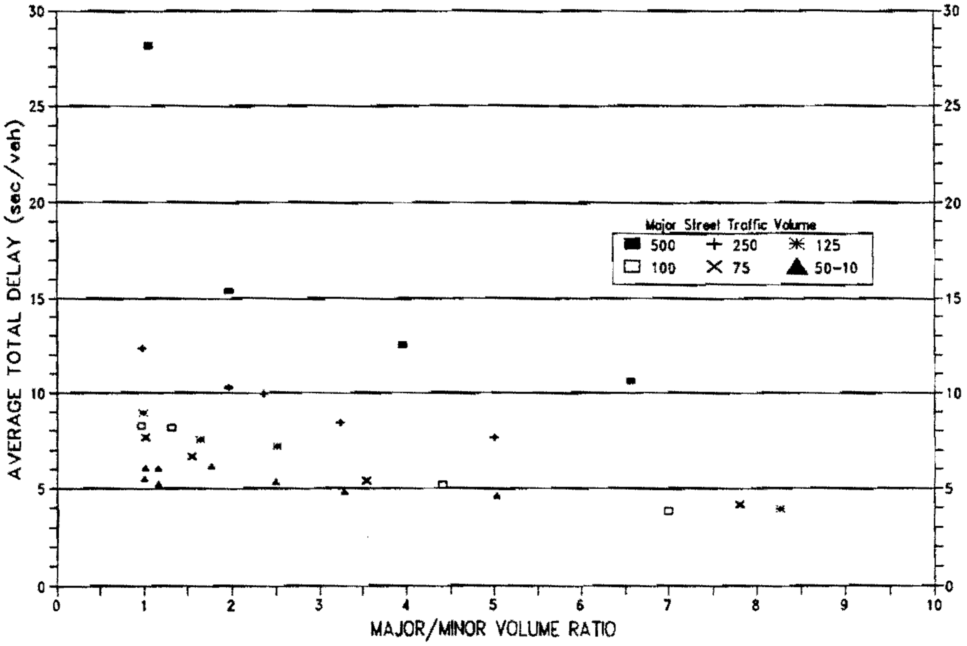


Figure G-14. Actuated for 5×2 Isolated Intersection

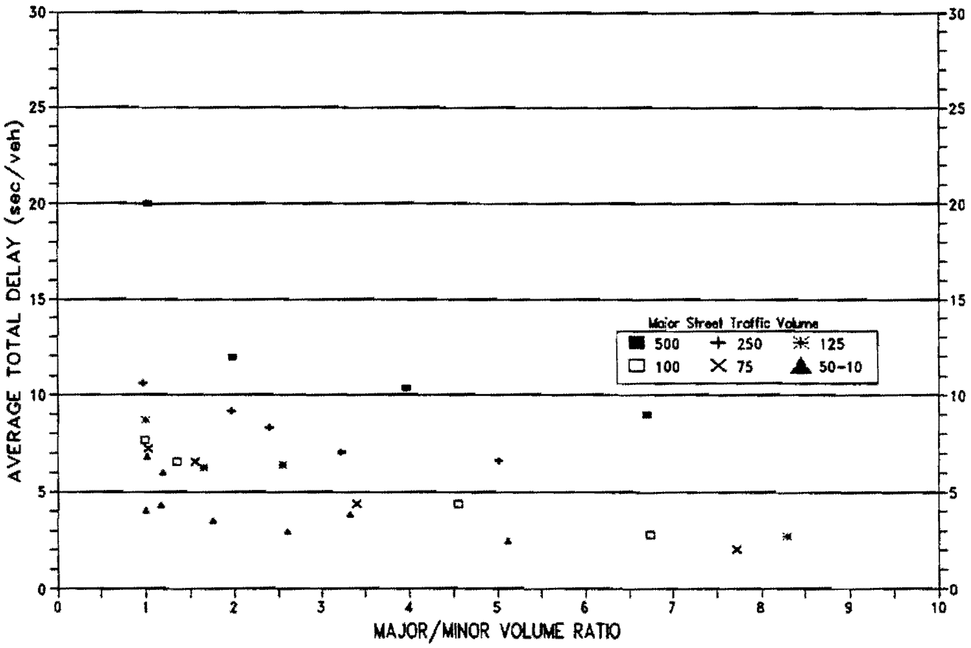


Figure G-15. Actuated for 4×2 Isolated Intersection

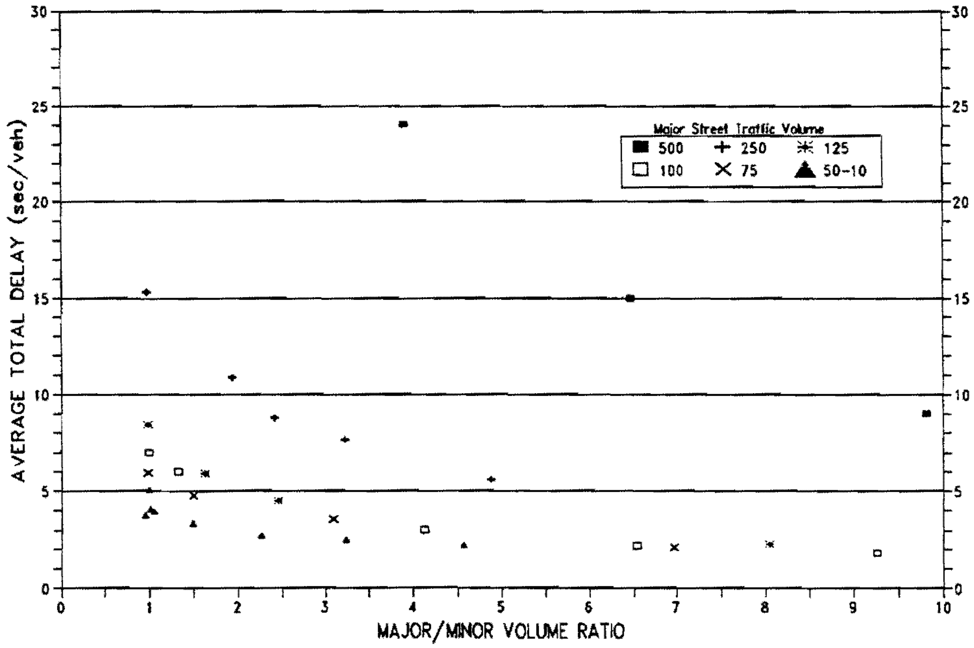


Figure G-16. Actuated for 2×2 Isolated Intersection

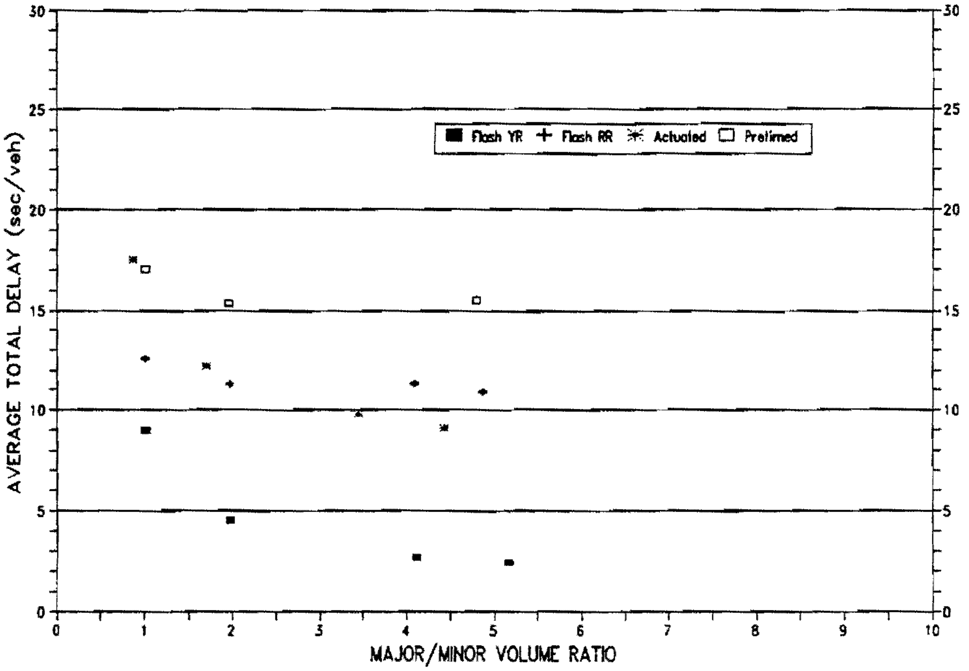


Figure G-17. Signal Control Comparison for 5×4 Isolated Intersection with 500 vph on Major Arterial

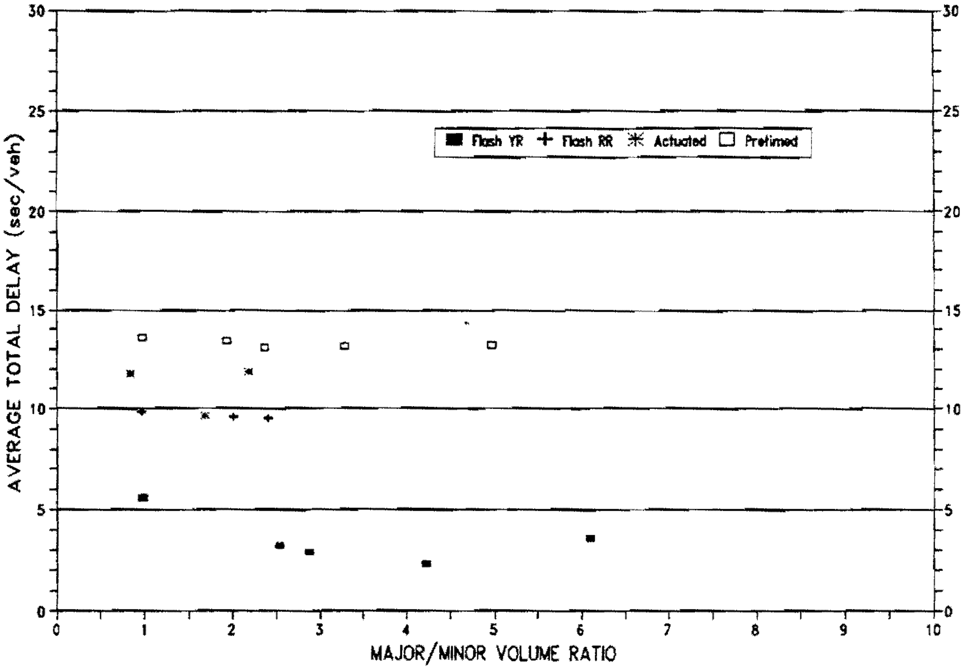


Figure G-18. Signal Control Comparison for 5×4 Isolated Intersection with 250 vph on Major Arterial

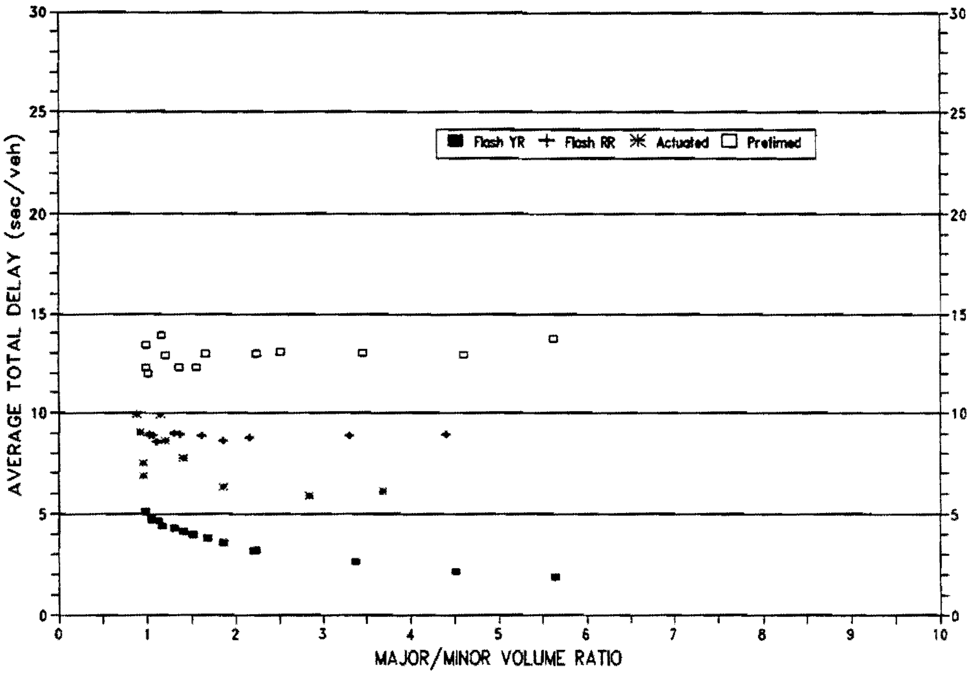


Figure G-19. Signal Control Comparison for 5×4 Isolated Intersection with less than 125 vph on Major Arterial

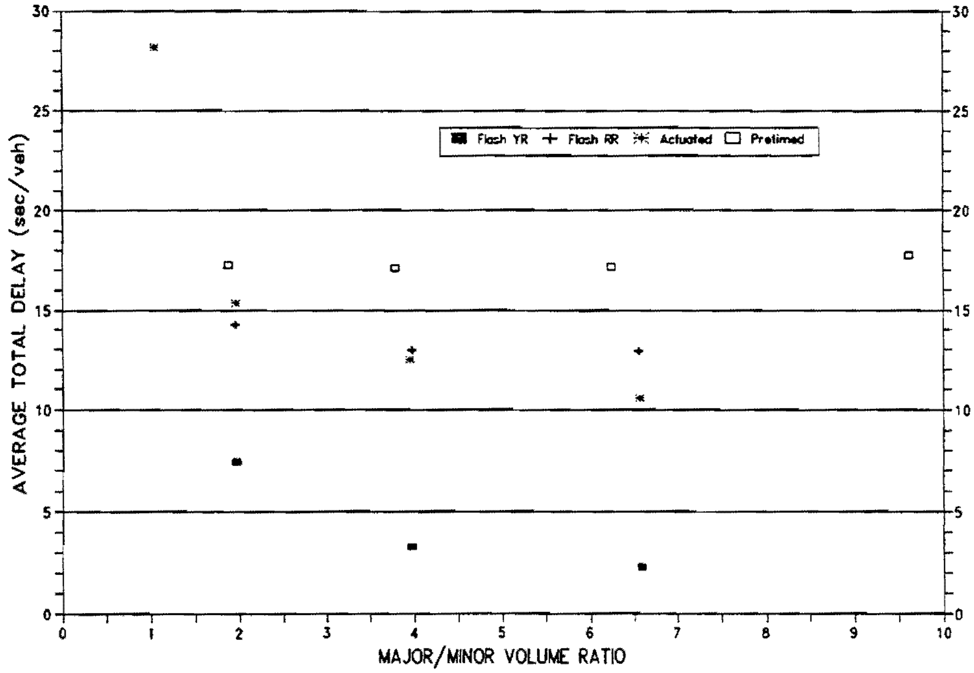


Figure G-20. Signal Control Comparison for 5×2 Isolated Intersection with 500 vph on Major Arterial

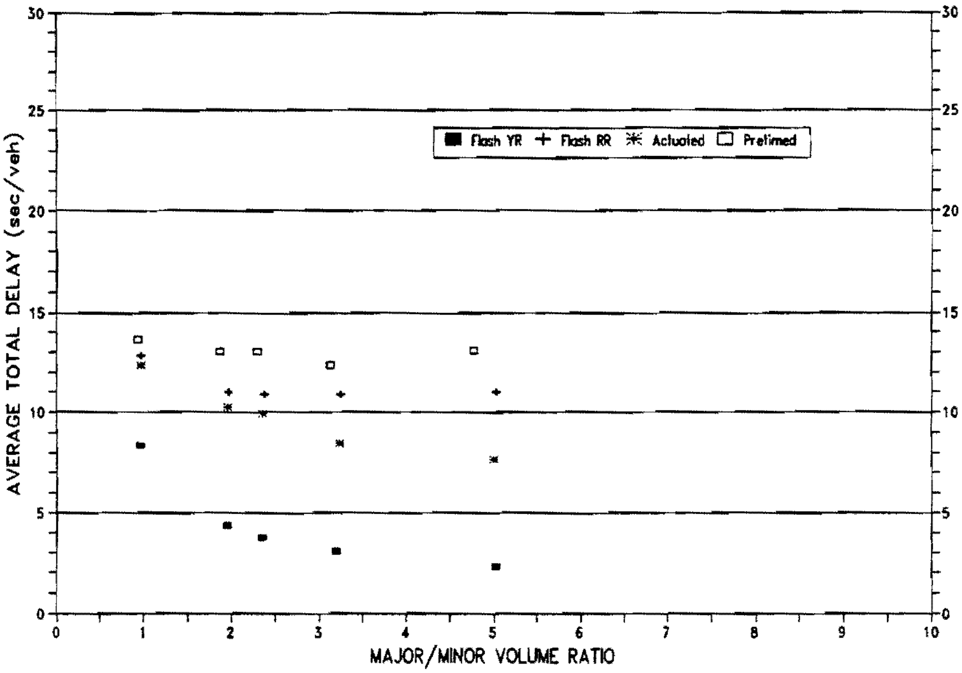


Figure G-21. Signal Control Comparison for 5×2 Isolated Intersection with 250 vph on Major Arterial

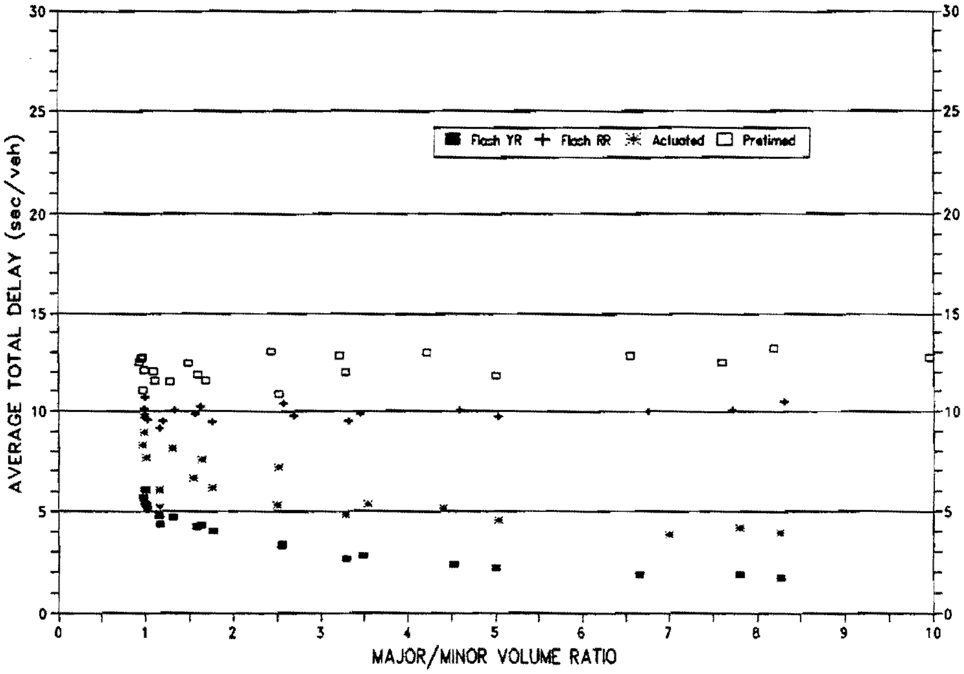


Figure G-22. Signal Control Comparison for 5×2 Isolated Intersection with less than 125 vph on Major Arterial

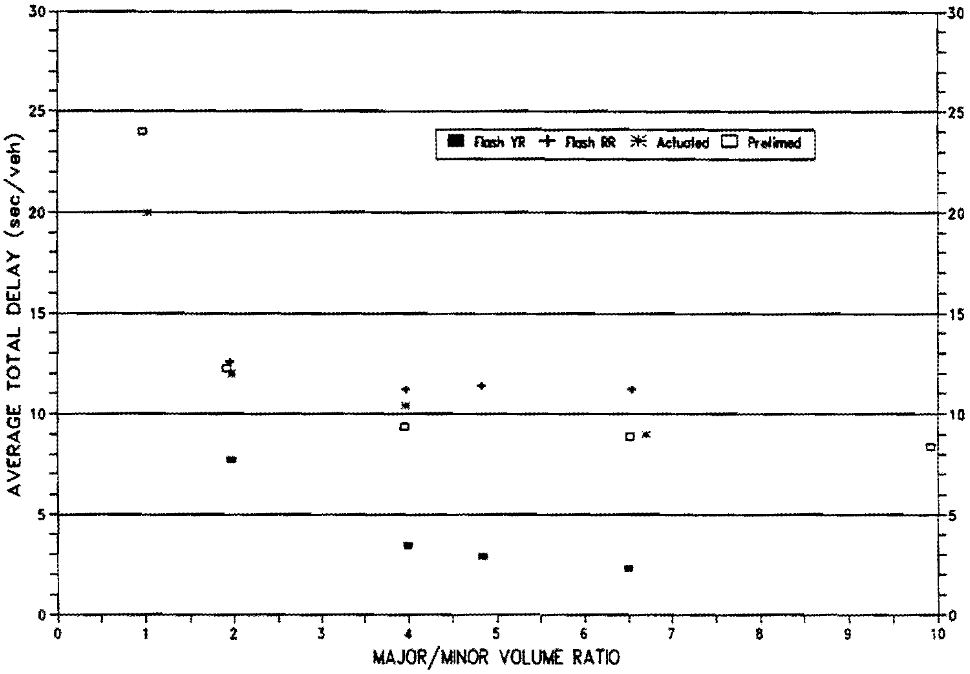


Figure G-23. Signal Control Comparison for 4×2 Isolated Intersection with 500 vph on Major Arterial

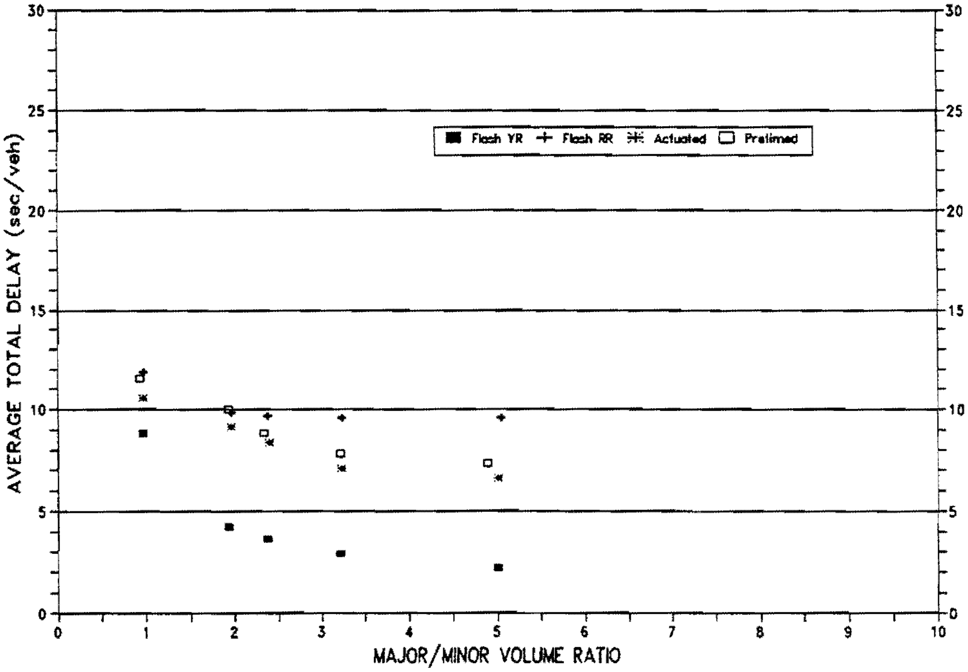


Figure G-24. Signal Control Comparison for 4×2 Isolated Intersection with 250 vph on Major Arterial

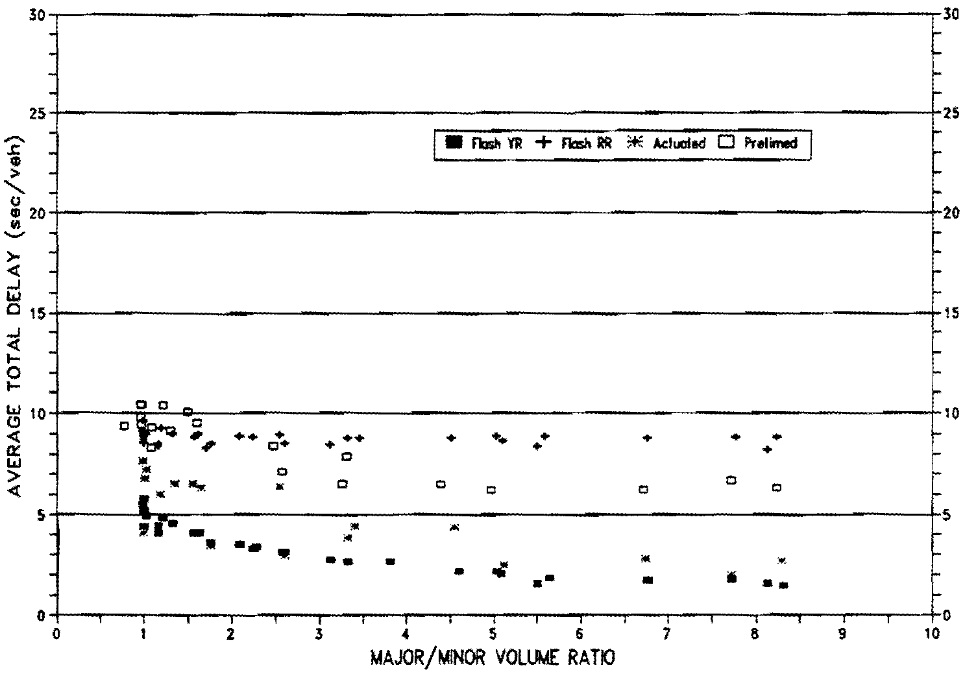


Figure G-25. Signal Control Comparison for 4×2 Isolated Intersection with less than 125 vph on Major Arterial

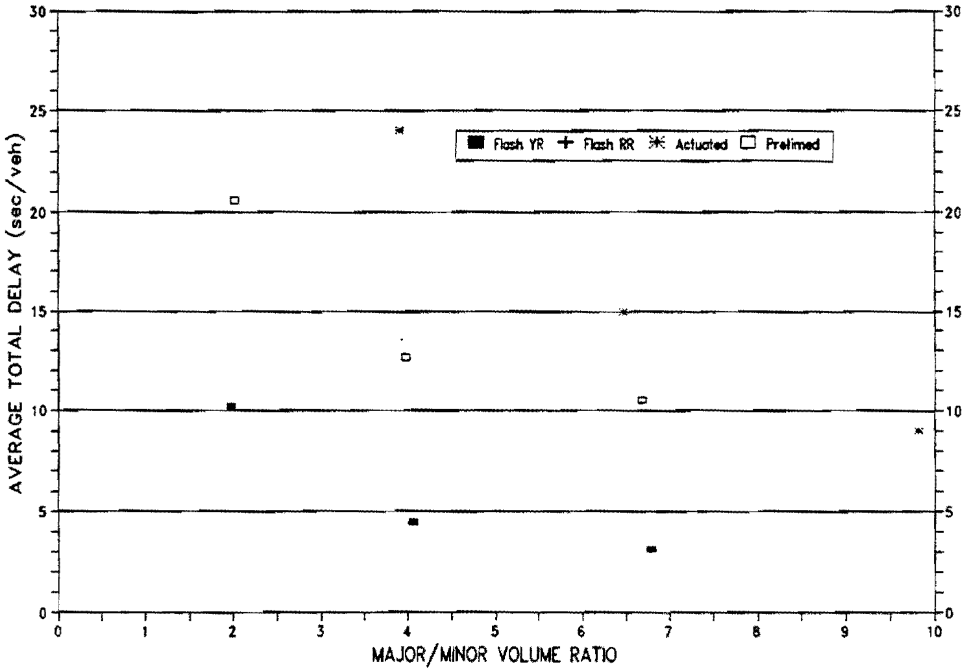


Figure G-26. Signal Control Comparison for 2×2 Isolated Intersection with 500 vph on Major Arterial

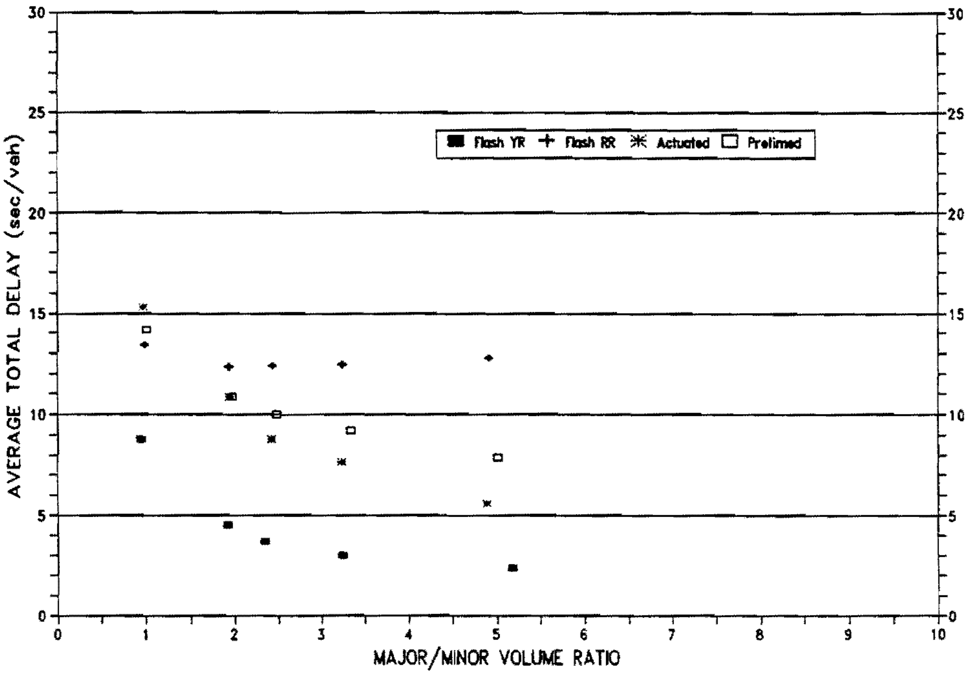


Figure G-27. Signal Control Comparison for 2×2 Isolated Intersection with 250 vph on Major Arterial

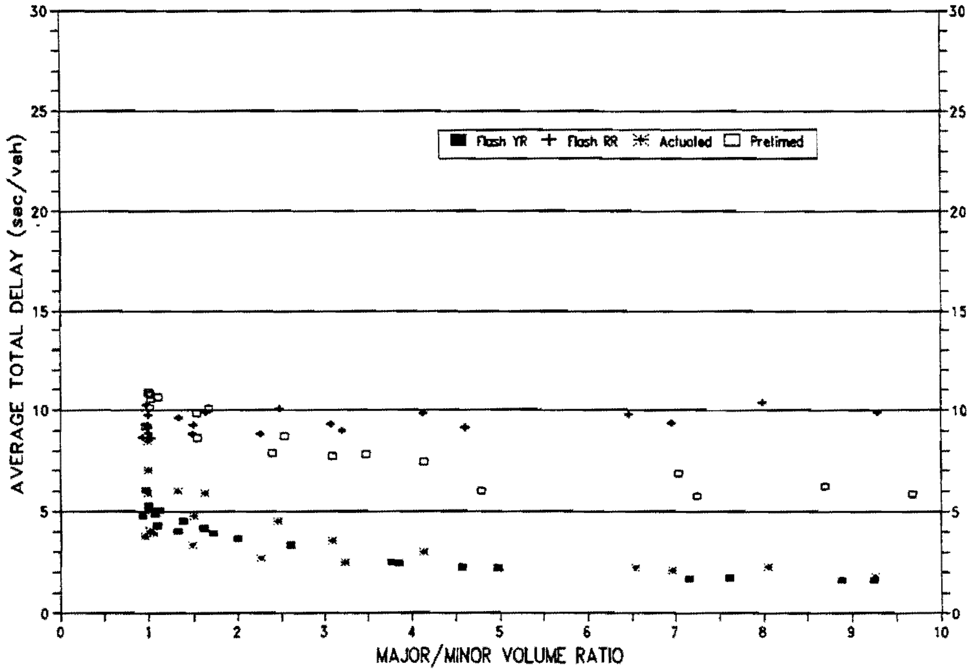


Figure G-28. Signal Control Comparison for 2×2 Isolated Intersection with less than 125 vph on Major Arterial

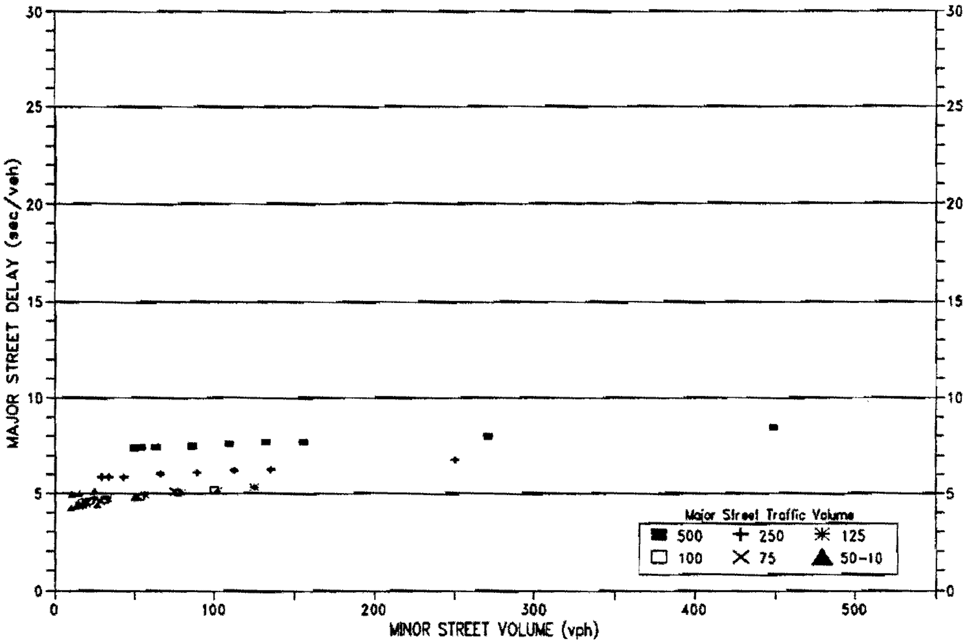


Figure G-29. Yellow/Red Flash for 5×4 Signal System

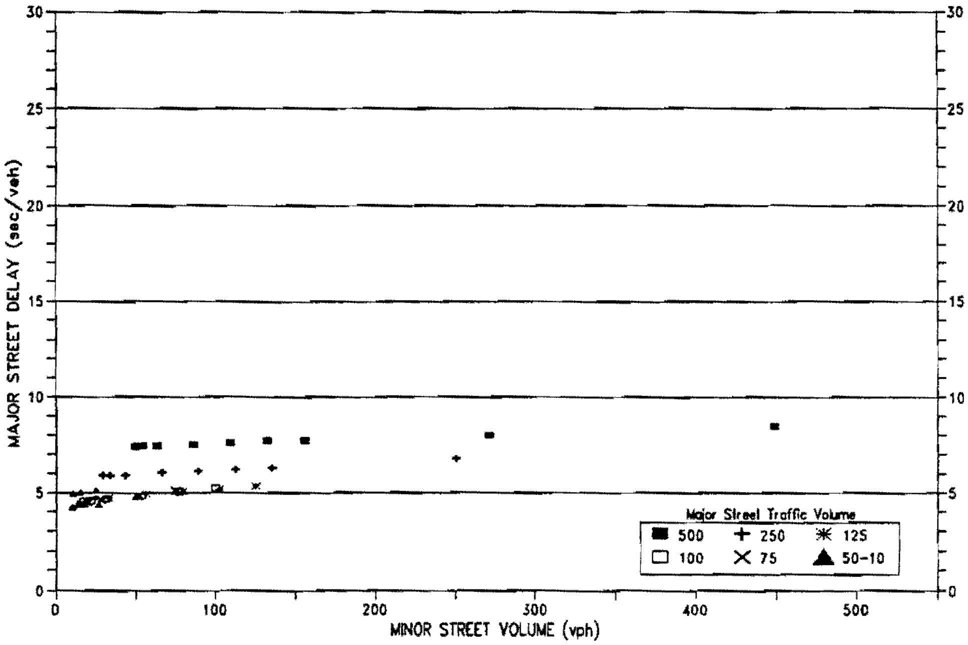


Figure G-30. Yellow/Red Flash for 5×2 Signal System

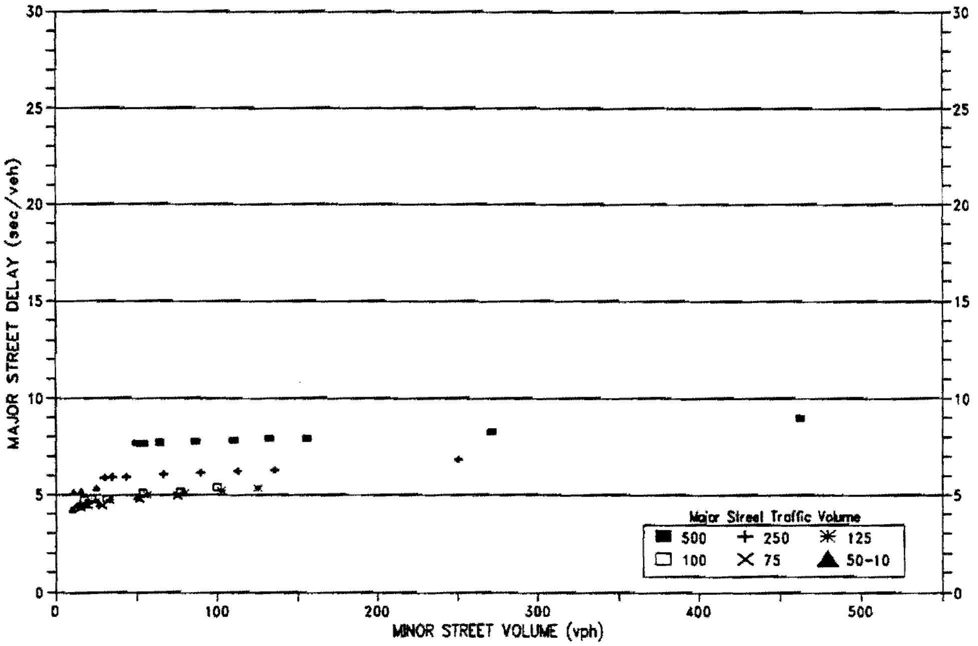


Figure G-31. Yellow/Red Flash for 4×2 Signal System

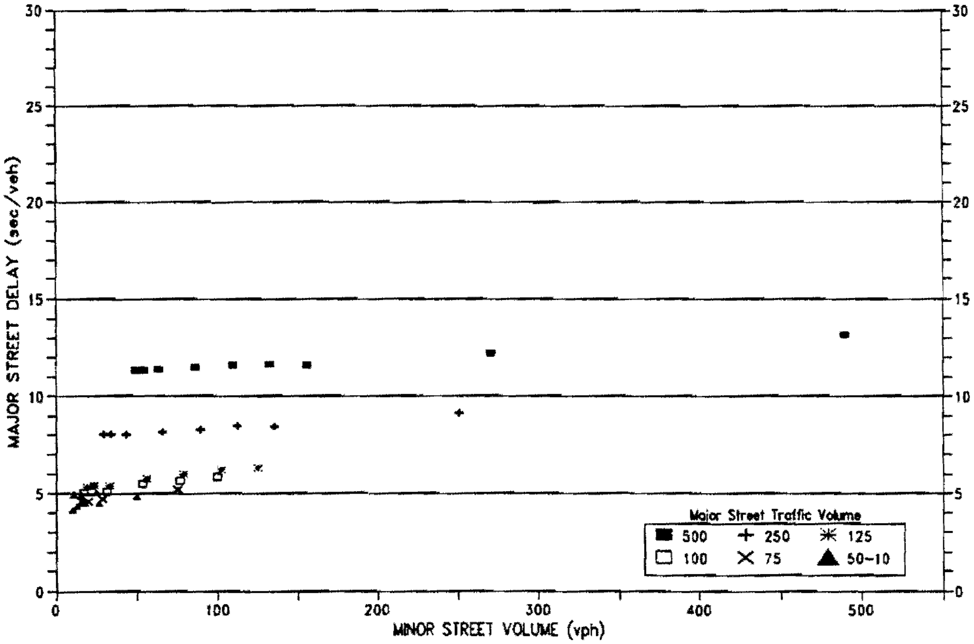


Figure G-32. Yellow/Red Flash for 2×2 Signal System

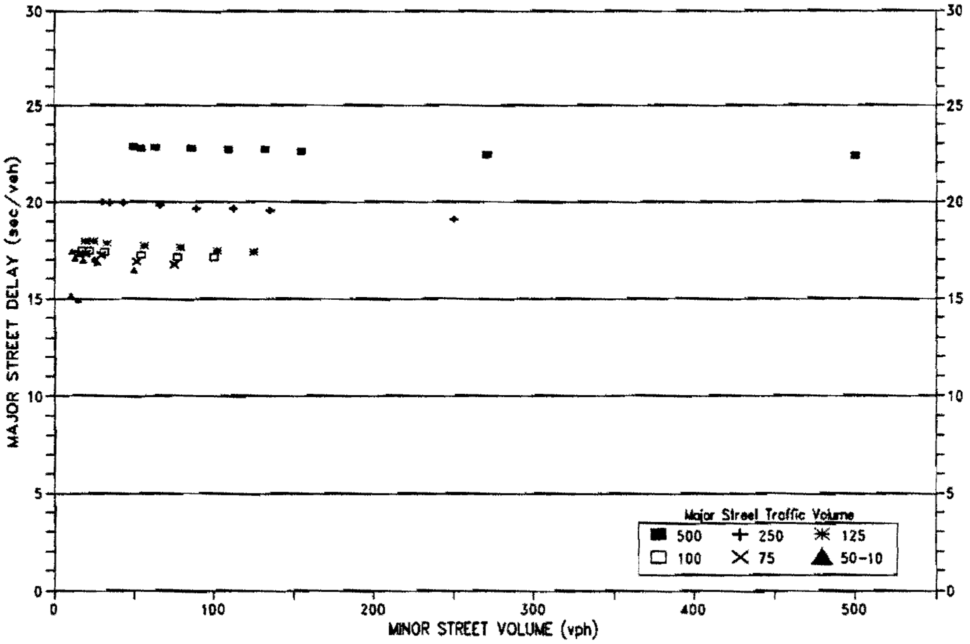


Figure G-33. Pretimed for 5×4 Signal System

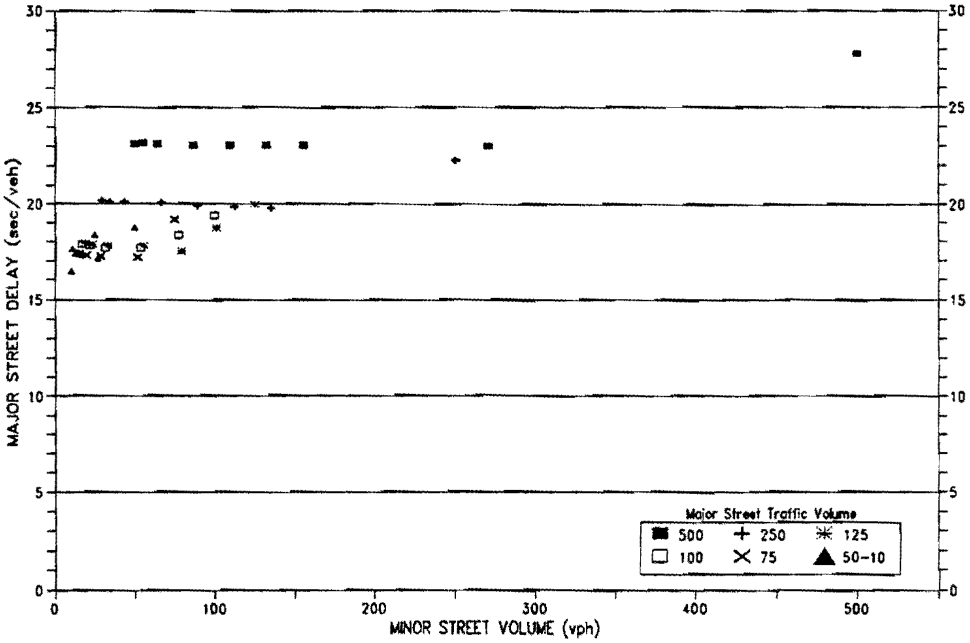


Figure G-34. Pretimed for 5×2 Signal System

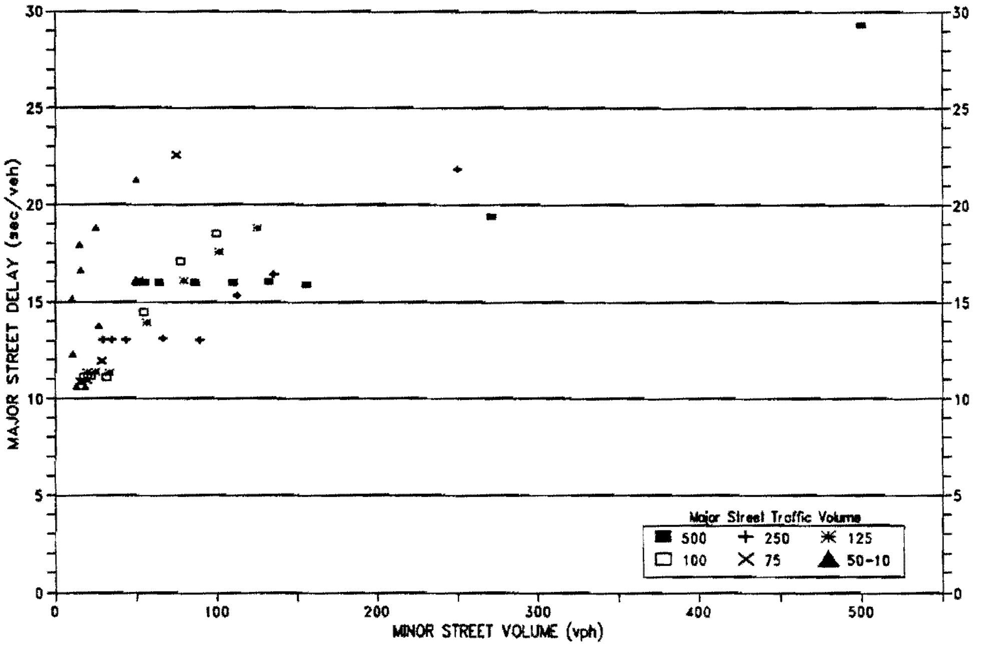


Figure G-35. Pretimed for 4×2 Signal System

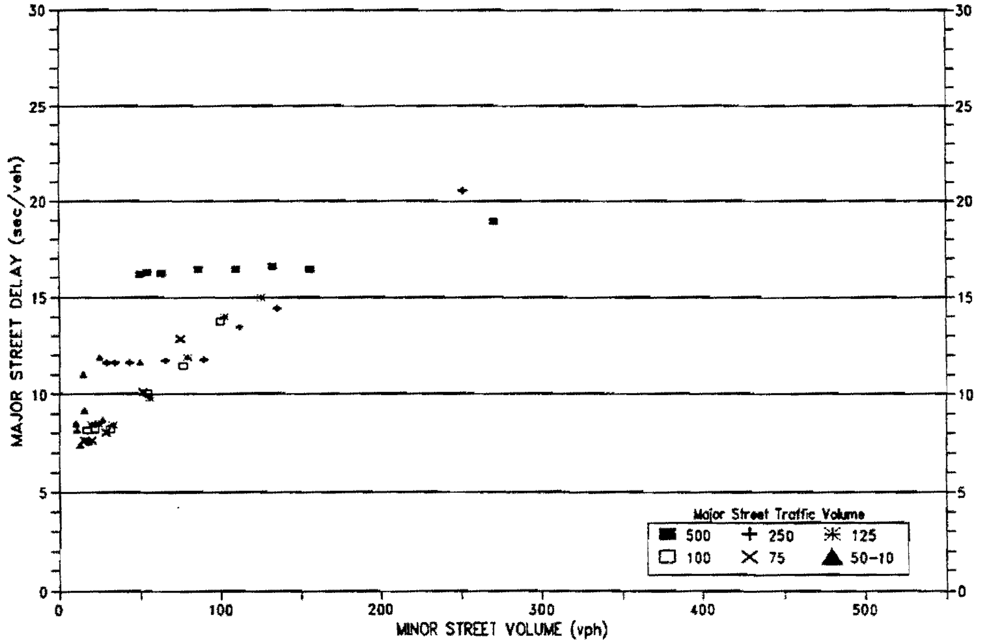


Figure G-36. Pretimed for 2×2 Signal System

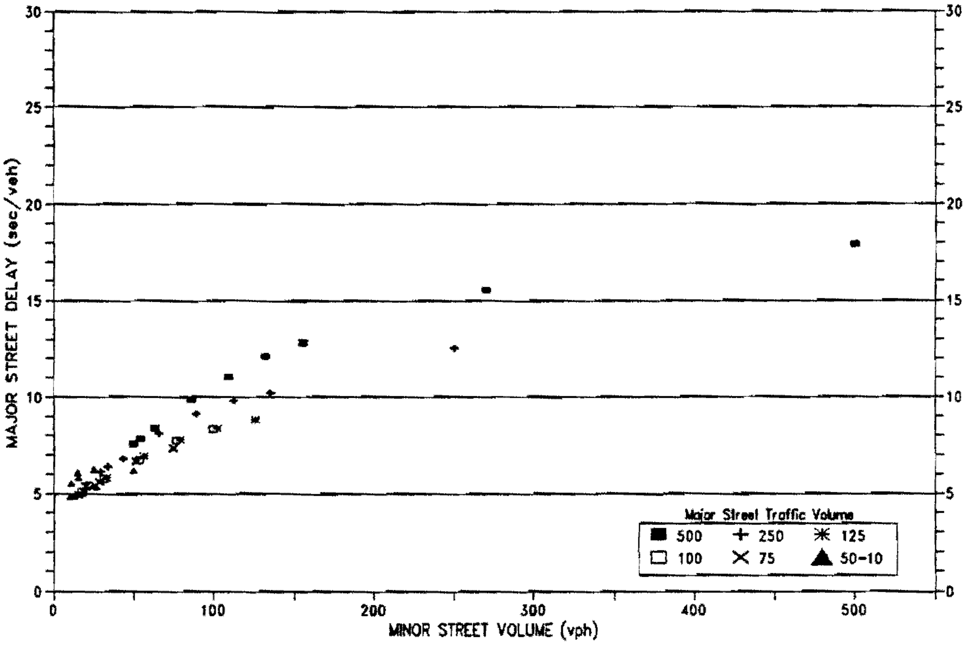


Figure G-37. Actuated for 5×4 Signal System

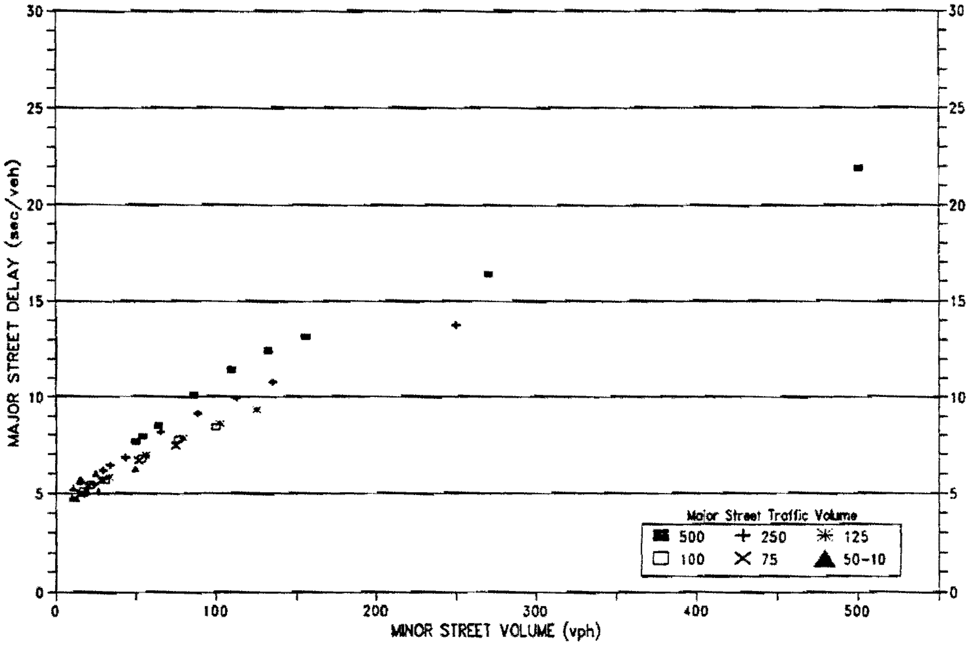


Figure G-38. Actuated for 5×2 Signal System

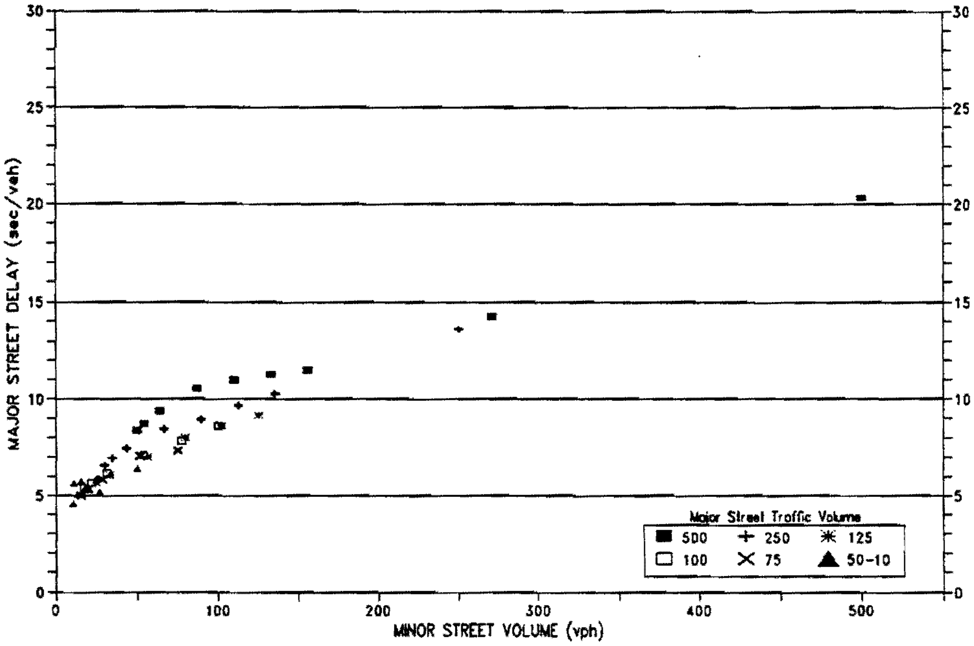


Figure G-39. Actuated for 4×2 Signal System

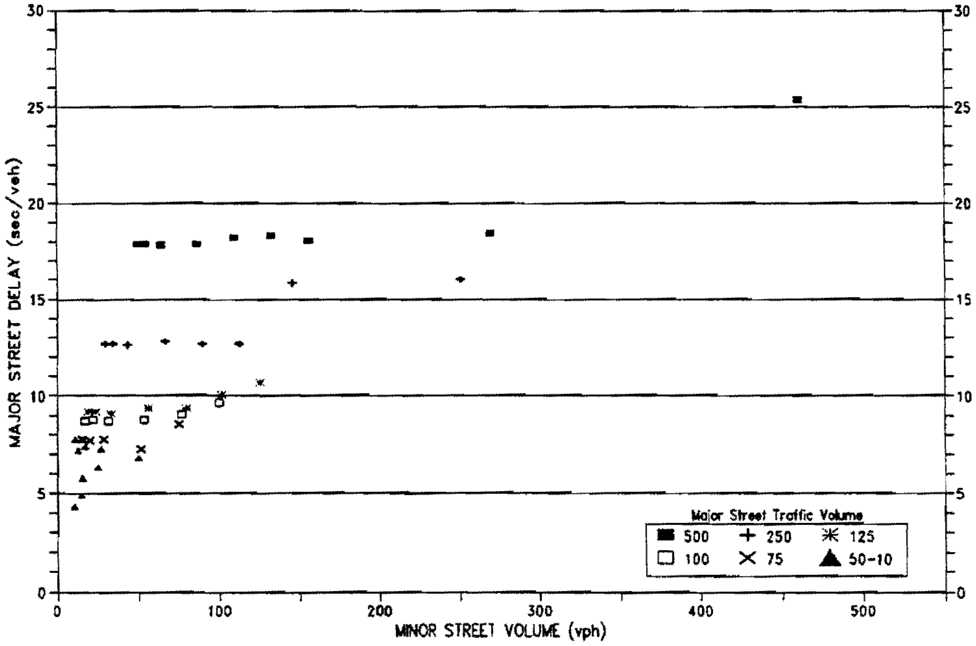


Figure G-40. Actuated for 2×2 Signal System

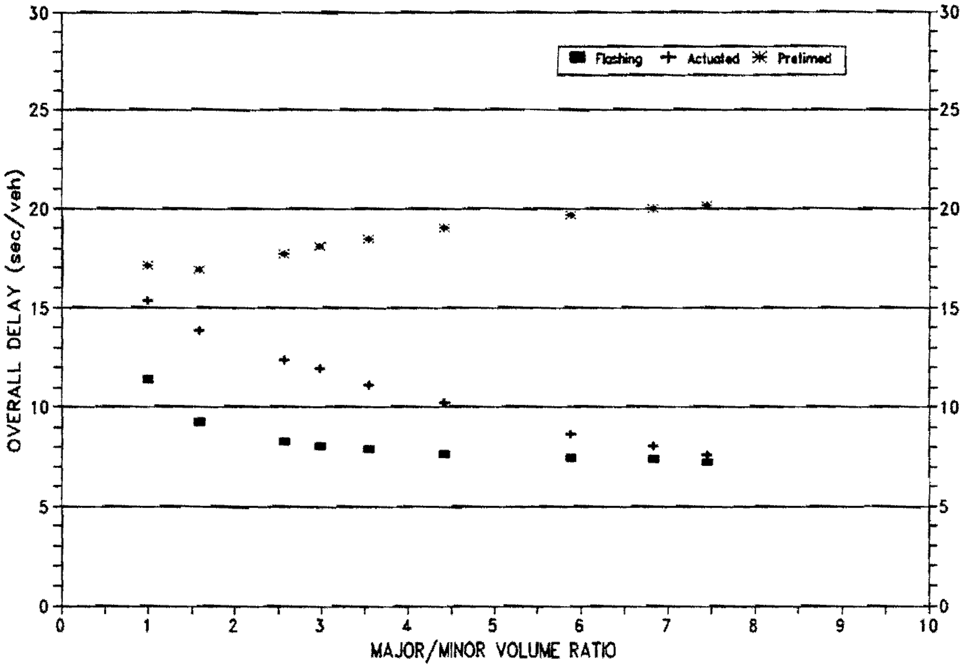


Figure G-41. Signal Control Comparison for 5×4 Signal System with 500 vph on Major Arterial

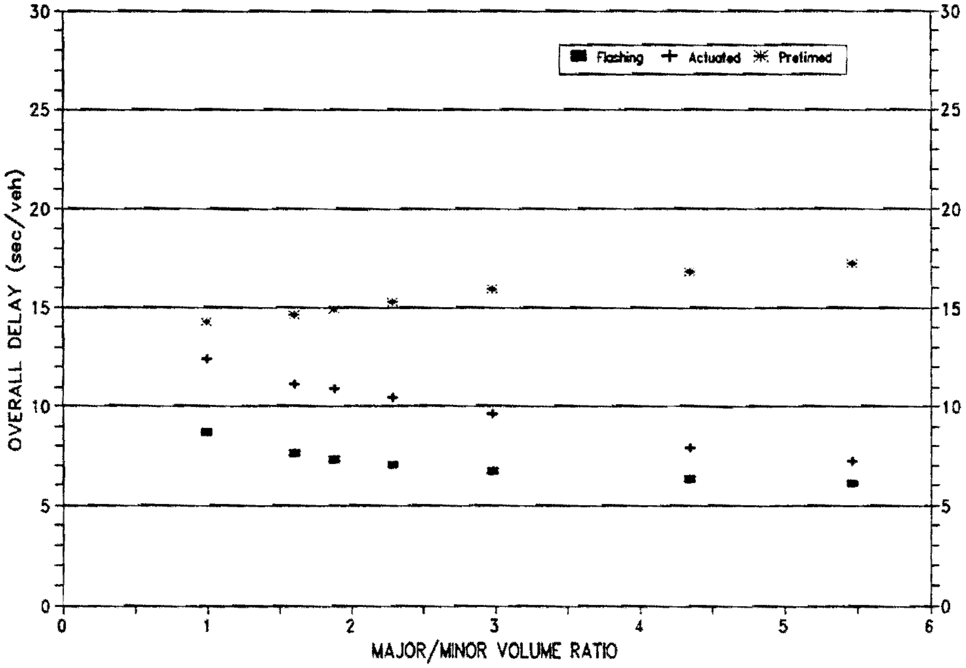


Figure G-42. Signal Control Comparison for 5×4 Signal System with 250 vph on Major Arterial

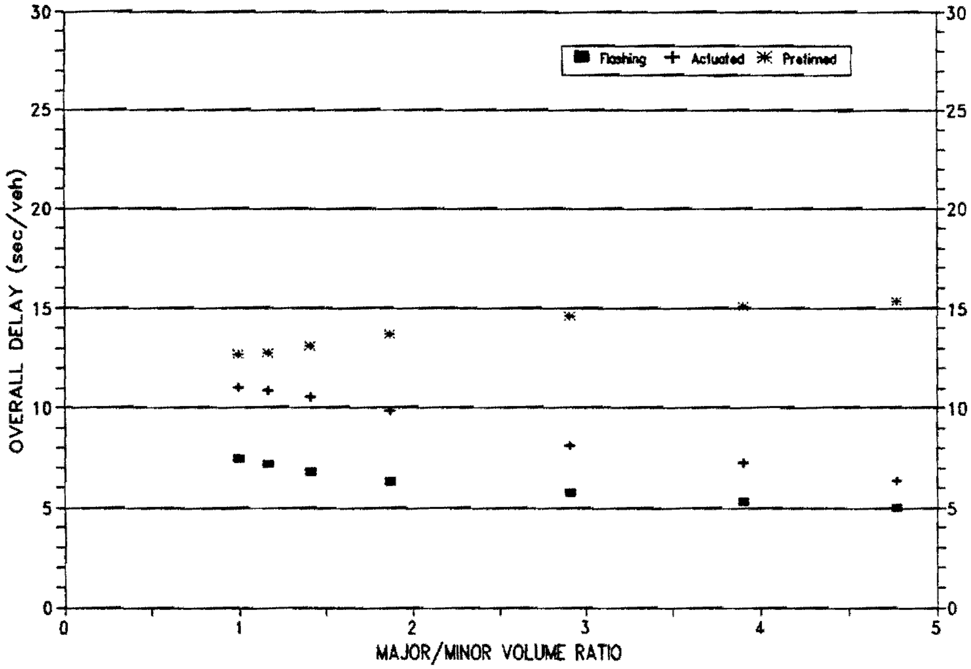


Figure G-43. Signal Control Comparison for 5×4 Signal System with less than 125 vph on Major Arterial

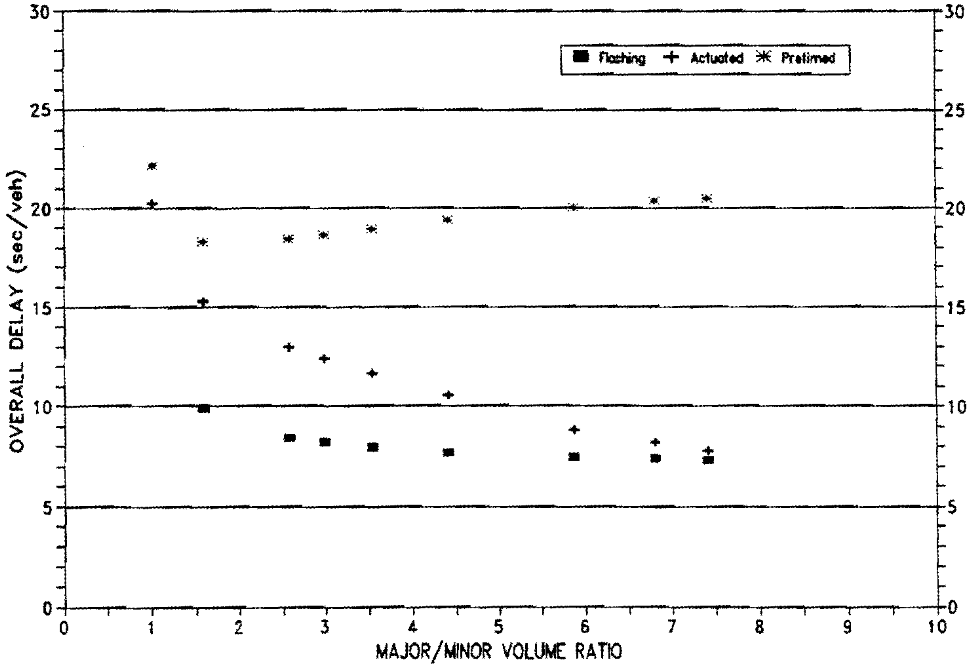


Figure G-44. Signal Control Comparison for 5×2 Signal System with 500 vph on Major Arterial

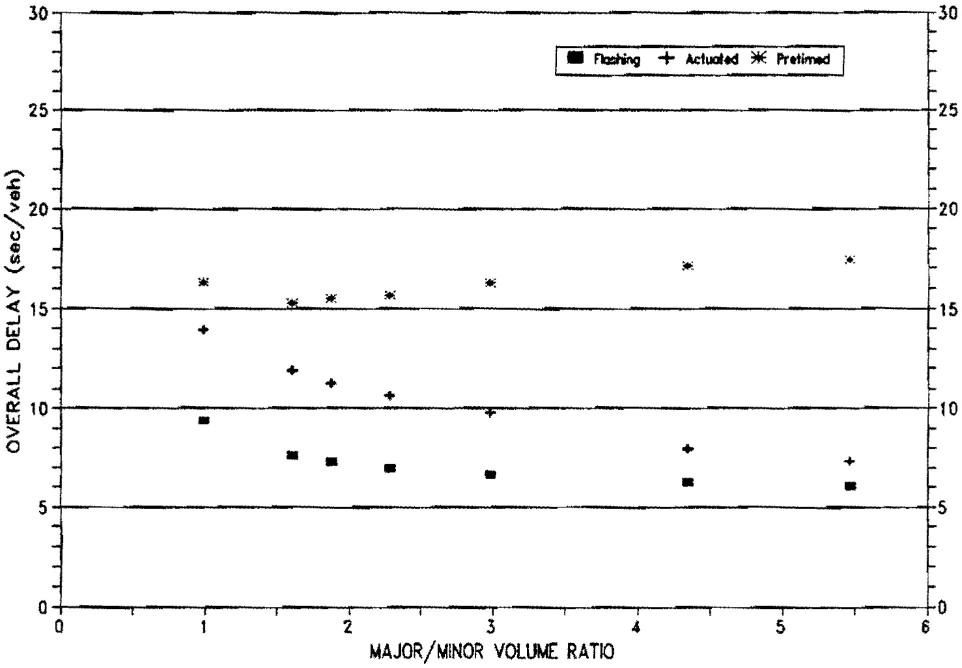


Figure G-45. Signal Control Comparison for 5×2 Signal System with 250 vph on Major Arterial

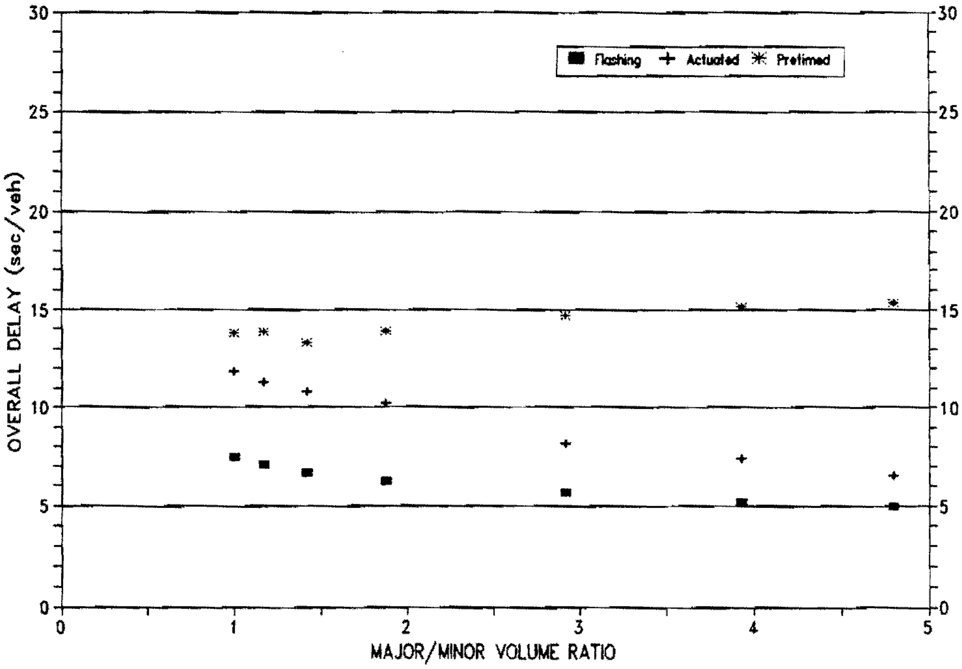


Figure G-46. Signal Control Comparison for 5×2 Signal System with less than 125 vph on Major Arterial

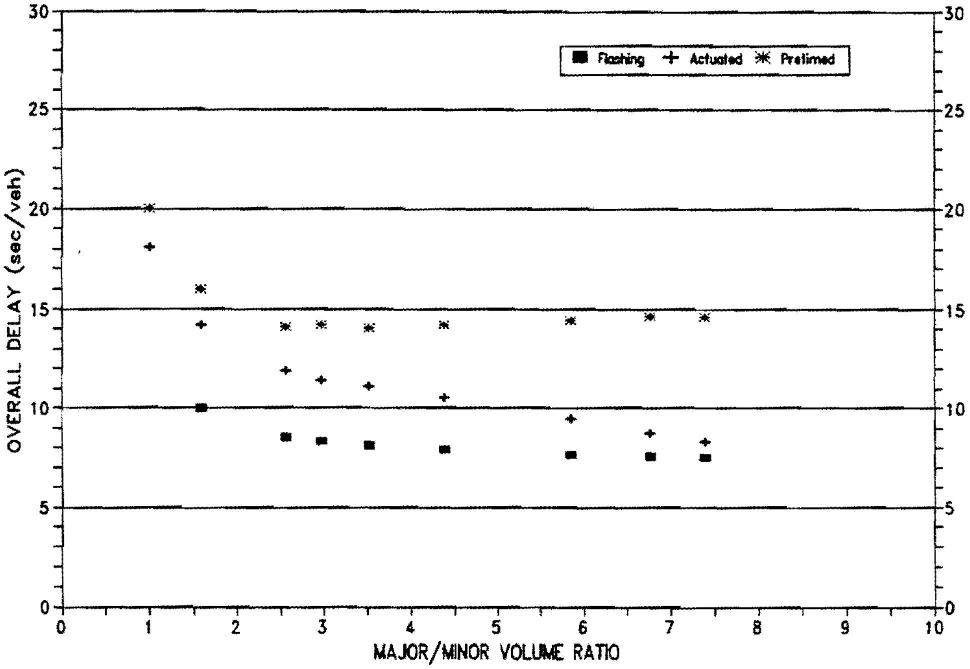


Figure G-47. Signal Control Comparison for 4×2 Signal System with 500 vph on Major Arterial

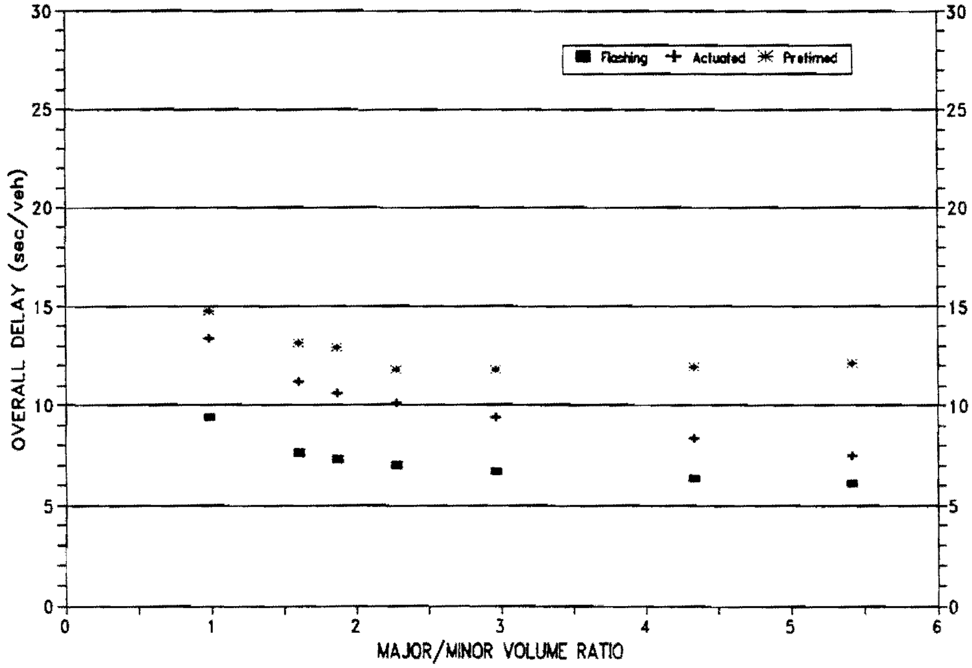


Figure G-48. Signal Control Comparison for 4×2 Signal System with 250 vph on Major Arterial

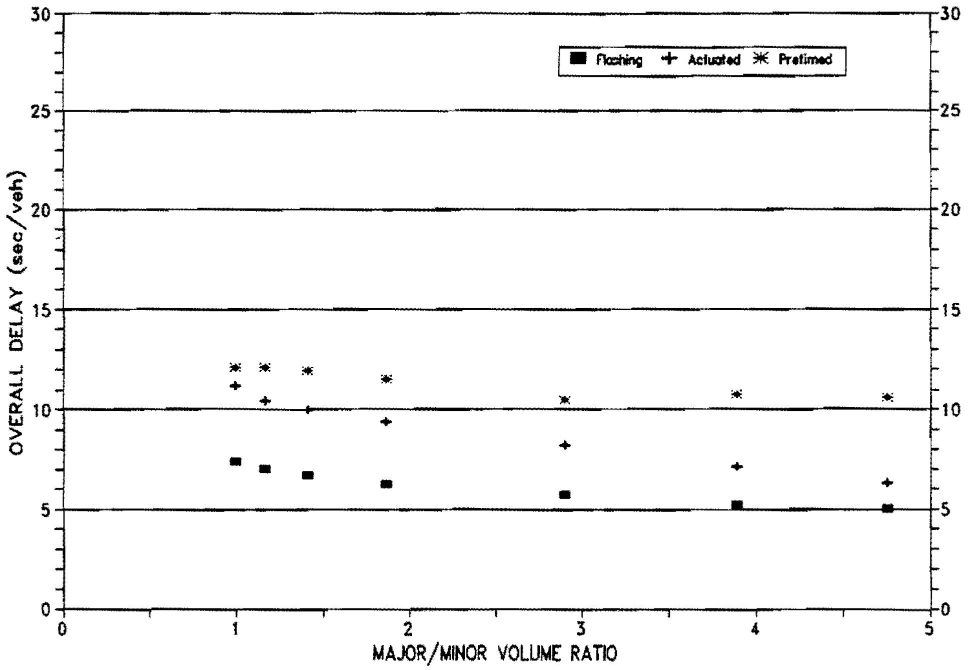


Figure G-49. Signal Control Comparison for 4×2 Signal System with less than 125 vph on Major Arterial

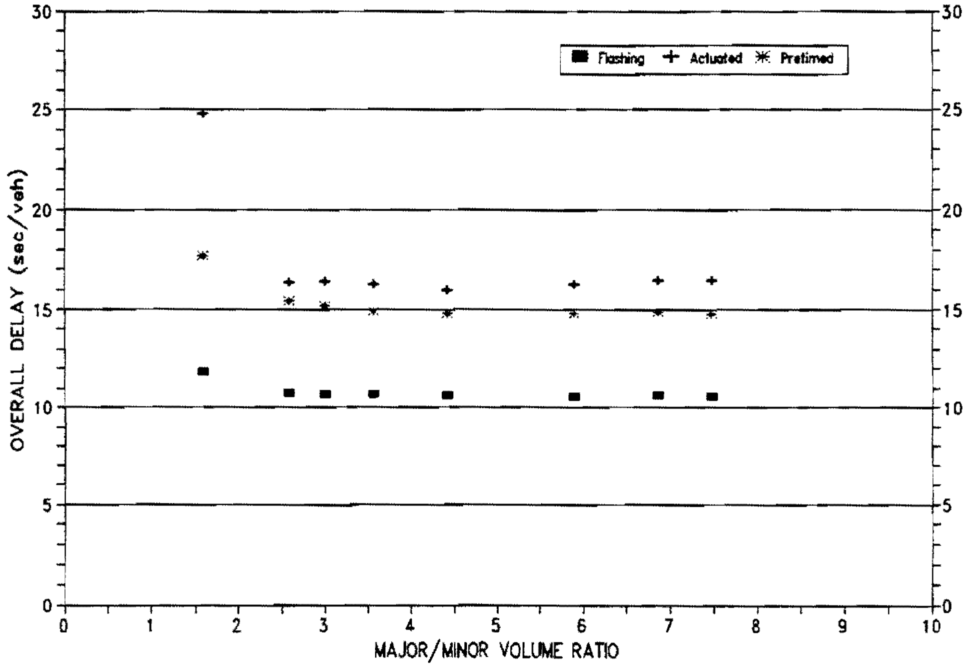


Figure G-50. Signal Control Comparison for 2×2 Signal System with 500 vph on Major Arterial

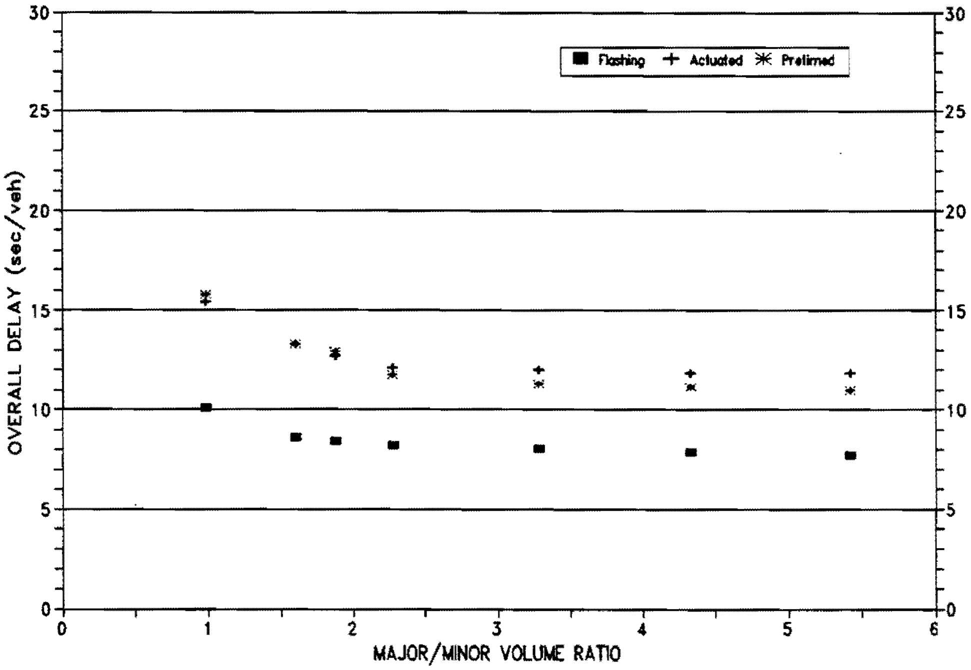


Figure G-51. Signal Control Comparison for 2×2 Signal System with 250 vph on Major Arterial

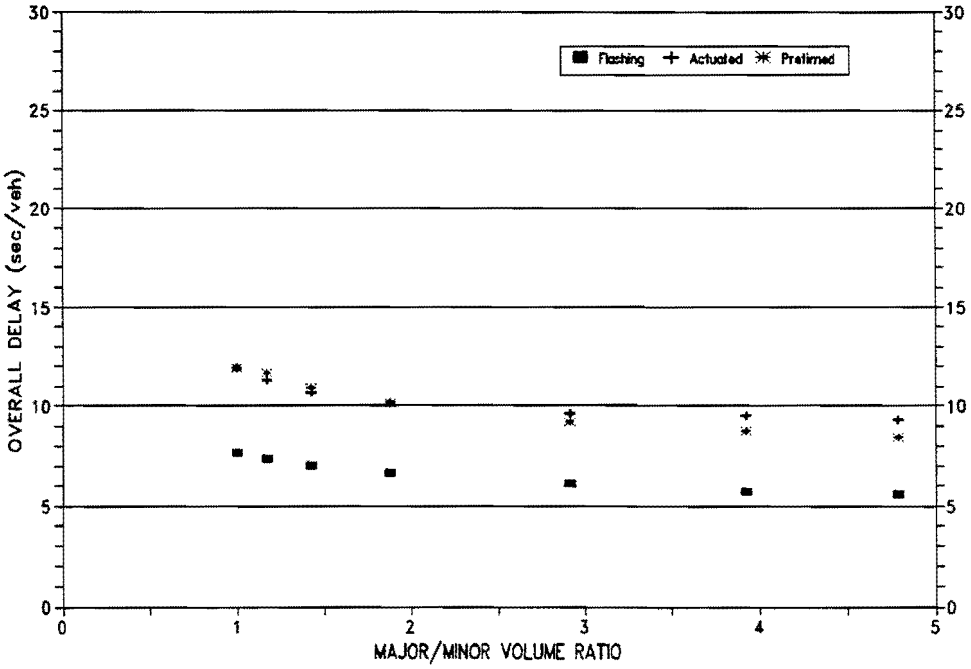


Figure G-52. Signal Control Comparison for 2×2 Signal System with less than 125 vph on Major Arterial