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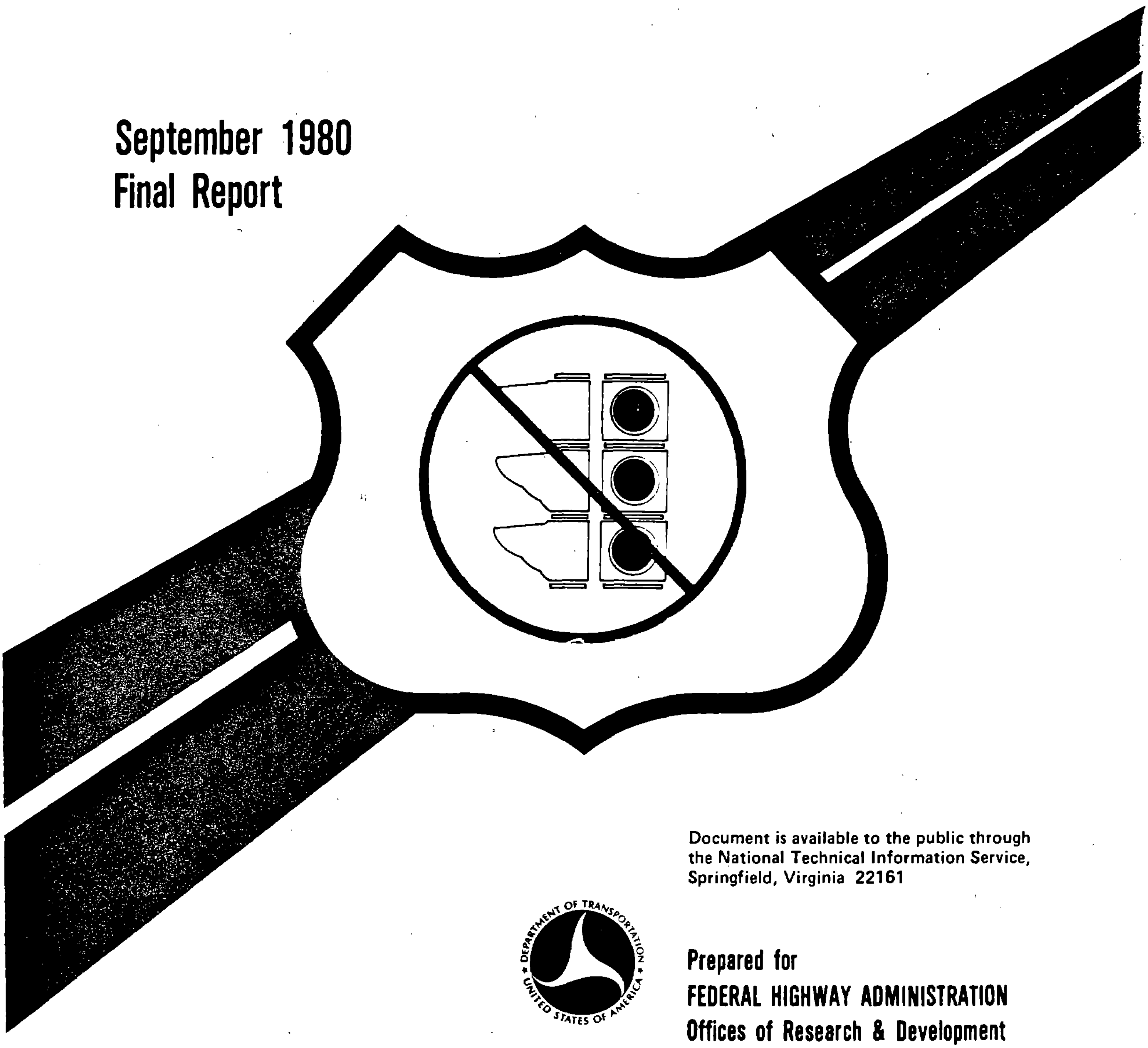
CRITERIA FOR REMOVING TRAFFIC SIGNALS, TECHNICAL REPORT

September 1980

Final Report



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FOREWORD

This research report provides the background and the analysis which led to the development of criteria and procedures for removing traffic signal installations. The report will be of interest to city and State traffic engineers who are involved in traffic signal reduction programs. The research was conducted as part of the Federally Coordinated Program (FCP) of Research and Development in Highway Transportation as a study in Project 1A--Traffic Engineering Improvements for Safety.

The criteria developed for removing traffic signals was based on an extensive review of experiences from 31 jurisdictions where signals at 226 intersections were successfully removed, and at 42 locations where the removal of the signals was attempted, but failed. The premise for the criteria was to identify measures which had been successfully applied for traffic signal removal and to determine the safety, delay, and fuel consumption impacts from such removals. The results of this research are presented in a "User's Guide," which is being published as an "Implementation Package."

Sufficient copies of this report are being distributed by FHWA to provide two copies to each regional office, two copies to each division office, and two copies to each State highway agency. The State and division office copies are being sent directly to each division office.

Charles F. Scheffey
Director, Office of Research

NOTICE

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16. Abstract
This report presents the results of a study to develop criteria that may be adopted as warrants for the removal of existing traffic control signals. The development of the signal removal criteria was based largely, as in a legal argument, on precedent. Those cases where positive impacts were realized by removing signals served to identify the criteria and conditions under which other signals should be removed. Likewise, cases involving negative impacts or unsuccessful removal attempts were reviewed to identify those conditions where signal removal should not be pursued. The methodology employed in this research was to compile the traffic signal removal experiences at over 200 intersections in 31 political entities, and to summarize and analyze this information to provide an objective base for the development of signal removal criteria. The decision process is designed to allow the traffic engineer to predict the expected impacts that will result from the removal of a traffic signal at a particular intersection. Knowing these probable impacts on intersection safety, traffic flow, energy consumption and costs, the traffic engineer can then make a sound decision concerning the removal of a signal. This volume documents the details of the signal removal criteria. A User's Guide is presented in another volume.

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TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

LIST OF TABLES (Continued)

LIST OF TABLES (Continued)

LIST OF FIGURES

CHAPTER I

INTRODUCTION AND SUMMARY

This is the final technical report documenting the procedures and results of the project entitled, "Criteria for Removing Traffic Signals." A separate document, "Users Guide for Removing Traffic Signals", provides a concise set of instructions and guidelines for applying the signal removal criteria and decision process developed in this project.

The project objective was:

> "to develop and field test criteria that may be adopted as warrants for the removal of existing traffic control signals."

The work, then, had the goal of developing rational criteria by which to justify the removal of traffic control signals where they should not be operating. The removal criteria apply only to signals that alternately assign right-of-way and not to flashing signals or beacons. The criteria are designed to allow the traffic engineer to predict the expected impacts that will result from the removal of a traffic signal at a particular intersection. Knowing these probable impacts on intersection safety, operations, energy conservation and costs, the traffic engineer can then make a sound technical decision concerning the removal of a signal. Recognizing the fact that traffic signal removal often involves institutional or political constraints, the signal removal criteria and decision process also include consideration of these issues in addition to the technical factors.

Another goal of the study was the development of signal removal procedural guidelines. The project thus included review and development of procedures which should be employed to carry out the actual implementation of the removal of a traffic control signal. These guidelines address such issues as advance public information needs, transition methods of changing control devices, and follow-up information needs.

In order for the results of this project to be of practical use, the principal findings, the signal removal criteria, and the procedural guidelines needed to be disseminated to the practicing traffic engineers who have the responsibility for making objective signal removal decisions and recommendations. To meet this need, a separate Users Guide was developed.

NEED FOR SIGNAL REMOVAL CRITERIA

Traffic control devices are used at intersections to regulate the flow of conflicting traffic streams. Since the traffic signal provides the maximum degree of at-grade intersection control, the general public has erroneously assumed it to be a panacea for all intersection safety problems. Thus, in many communities, due to a lack of transportation engineering expertise, or political pressure, or both, traffic control signals have been installed at intersections where they are not warranted. The result has been an increase in stops, delay and fuel consumption and in many cases, an increase in the number of accidents.

While the relationship between new traffic signals, intersection accidents and operations has been widely studied, very little was known about the impacts of traffic signal removal. The signal removal study was initiated by the Federal Highway Administration (FHWA) to identify what conditions and criteria have been used throughout the United States for the removal of traffic signals and to develop criteria that may be adopted as warrants for the removal of existing traffic signals.

The development of the signal removal criteria was based largely, as in a legal argument, on precedent. Those cases where positive impacts were realized by removing signals served to identify the criteria and conditions under which other signals should be removed. Likewise, cases involving negative impacts or unsuccessful removal attempts were reviewed to identify those conditions where signal removal should not be pursued.

IMPACTS STUDIED

Four major impacts of signal removal were of greatest concern: safety impacts, fuel consumption, traffic flow impacts, and cost impacts.

The effects on accident frequency and severity are very important because of the common argument of signal removal opponents that accidents and injuries will increase if a signal is removed. The development of signal removal criteria obviously must include a good understanding of the actual accident impacts.

The impacts on stops and delays, and the corresponding impact on fuel consumption, are increasingly important concerns.

The cost savings accruing to the traffic engineering agency as a result of replacing signals with stop control is also a major factor motivating decisions to remove signals. To jurisdictions operating with austere budgets this factor can be of paramount importance.

CASE STUDIES

The study of the impacts of signal removal relied heavily on case study data from 31 jurisdictions across the United States that had removed traffic signals and documented the results. Enough data were collected from the case study sites to establish the following signal removal data base:

- 5 rural signals converted to 2-way stop
- 5 rural signals converted to multi-way stop
- 191 urban signals converted to 2-way stop
- 26 urban signals converted to multi-way stop
- 42 signals where signal removal attempts failed.

ACCIDENT IMPACTS

The size of the rural intersection data base was too small to be considered representative. Therefore, the analysis focused on the impacts of signal removal in urban areas.

Conversion to Multi-Way Stop Control

For the group of 26 intersections converted to multi-way stop control, there was a decrease in the average annual accident frequency of more than one accident per year. Annual accident frequency was reduced 60 percent from 1.70 to 0.68 accidents per year, a statistically significant change. Annual injury accident frequency per intersection was also reduced significantly from 0.50 to 0.19.

It must be emphasized that all the intersections in this group had characteristics favorable to multi-way stop control: i.e., low traffic volumes and relatively balanced major road and side road flows. These results should not be interpreted to mean that multi-way stop control should always be used when signals are removed. Indeed, in a majority of cases, side road volumes are much lower than main road volumes at candidate locations, and multi-way stop control is not an appropriate alternative.

Conversion to Two-Way Stop Control

Signals were replaced by two-way stops at 191 of the urban case study intersections. The average result was a small decrease in both total accidents (from 2.46 to 2.38 per year) and injury accidents (from 0.70 to 0.63). These changes were not statistically significant.

Right angle accidents increased 51 percent and rear-end accidents decreased 49 percent, as expected, following signal removal and replacement by two-way stop control. These changes were offsetting and did not result in any significant net change in either total collisions or injury accidents.

Factors Influencing Accident Impacts

There was a wide dispersion of accident impacts of signal removal at the individual intersections converted to two-way stop control. The study explored which intersection characteristics had a significant influence on whether accident frequency increased or decreased following signal removal.

Three variables were found to have a significant effect on the accident outcome of signal removal:

1. Adequacy of side street sight distance.
2. Traffic volume magnitude (i.e., as measured by the number of hours per day when traffic volumes satisfy at least 60 percent of the signal installation traffic volume warrant #1).
3. Average annual accident frequency at the intersection prior to signal removal.

Predicting Accident Impacts

Prediction models for estimating the accident impacts of replacing traffic signals with two-way stop control were developed from the case study data using two different methods -- cross-classification and multiple regression. Both methods used the same two independent (predictor) variables: (1) intersection volume magnitude as measured by the number of hours meeting 60 percent of signal installation volume warrant #1 and (2) the "before" annual accident frequency. The multiple regression approach proved to be a somewhat better prediction method than the cross-classification approach.

Both prediction methods indicate that higher volume intersections are associated with increased accidents following signal removal, and vice versa. Intersections with low accident frequencies prior to signal removal tend to have increased accident frequency after removal, and vice versa. Intersections that are good candidates for signal removal are ones with relatively low traffic volumes and annual accidents of at least 2 or more per year.

Impact of Inadequate Corner Sight Distance

Signal removal experience at intersections with inadequate corner sight distance was separately considered. The case study data set contained only 15 such intersections. For these, the average annual accident frequency following signal removal rose dramatically from 2.03 to 4.85 per year. Annual average injury accidents doubled from 0.60 to 1.21 per intersection. These increases can be fully attributed to the increased risk of right angle collisions.

IMPACTS ON DELAYS, STOPS, AND FUEL CONSUMPTION

Traffic signal removal results in substantial impacts on intersection delays, stops, and the resulting excess fuel consumption. Empirical data on intersection stops, delays, and fuel consumption were not available from the case study data base; consequently, analytical estimates of these impact variables were made for a range of intersection types and traffic volumes.

Conversion to Two-Way Stop Control

Replacing unjustified signals with 2-way stop control has an especially beneficial effect in reducing intersection delays, stops, and fuel consumption. The range of impacts per vehicle is relatively consistent for a wide range of intersection conditions.

When signals at 4-way intersections are replaced by 2-way stop signs, the following approximate impacts occur:

- Total delay per vehicle is reduced by about 10 seconds.
- Idling delay per vehicle is reduced by about 5 to 6 seconds.
- Stops are reduced from about 50 percent of total intersection traffic to about 20 to 25 percent or even less if side road volumes are low in relation to total intersection volume.
- Excess fuel consumption due to intersection stops and delays is <u>reduced</u> by about 0.002 gallons per vehicle.

In the case of similar volumes at a T-intersection, the reductions in delays, stops, and fuel consumption would be slightly greater.

The approximate order of magnitude of the <u>daily</u> impacts of signal removal and replacement by 2-way stop control can be estimated by multiplying the preceding "per-vehicle" impacts by total 24-hour traffic volume. This would normally be computed for typical <u>weekday</u> volumes although, at some locations, the weekend volumes <u>may be</u> critical. Annual impacts can be approximated by multiplying the total weekday impact estimates by 320.

For example, with respect to excess fuel consumption, at an intersection with typical weekday traffic volume of 10,000 per day, traffic signal removal and replacement by 2-way stop control would save approximately:

0.002 X 10,000 = 20 gallons per weekday

Corresponding annual energy conservation at the single intersection would be:

20 X 320 = 6,400 gallons per year.

Conversion to Multi-Way Stop Control

When an unjustified traffic signal is replaced by multi-way stop control at a four-way intersection with moderate traffic volumes and fairly evenly balanced main road and side road flows, the following approximate impacts occur.

- Total delay per vehicle does not change by much.
- Idling delay per vehicle is reduced by about 5 seconds.
- Stops always equal 100 percent of total traffic, approximately double that experienced under signal control.
- Excess fuel consumption is increased by about 0.0015 gallons per vehicle.

At an intersection serving 10,000 vehicles per day on an average weekday, the daily increases in fuel consumption would total roughly

10,000 x 0.0015 = 15 gallons per weekday.

Annual increases in energy would equal about:

15 x 320 = 4,800 gallons per year.

Nomographs and Worksheets

A set of nomographs are included on pages 64-75 estimating intersection delays, stops, and excess fuel consumption for a wide range of combinations of main road and side road hourly volumes. The nomographs permit estimates of the impact variables under traffic signal control and two-way stop control for 6 different common intersection design types.

A standard worksheet is also included for systematic calculations of the daily impacts of signal removal from the nomograph estimates of hourly impacts.

COST SAVINGS OF SIGNAL REMOVAL

Traffic signal removal is one of those rare activities that saves the money of the traffic engineering agency. For a typical uncomplicated existing signalized intersection, the comparative annual costs of continued signal operation versus signal removal and replacement with 2-way stop control are estimated as follows:

Annual Costs of Continued Signal Operation

Electrical costs	=	$ 250
Maintenance	=	1,100
Traffic signal timing	=	50
Total		$1,400

Annual Costs of Signal Removal

(Equivalent annual costs for 15 year period @12 percent interest)

Remove signal	=	$295
Install stop signs	=	25
Sign maintenance	=	20
Total		$340

The annual savings in agency costs resulting from signal removal for this typical case is $1,060 per year. It is emphasized that costs of signal removal and of continued signal operation are highly dependent on local conditions and on the unique features of a given signalized intersection.

SIGNAL REMOVAL CRITERIA AND DECISION PROCESS

The results of this research were utilized to develop a recommended set of signal removal criteria and an associated decision process. The process is divided into two stages: (1) a preliminary screening to determine if detailed consideration of signal removal is worthwhile and (2) a detailed analysis of signal removal impacts.

In the end, the signal removal decision is, by necessity, a combination of quantitative and qualitative considerations. The findings of this project, as reflected in the proposed signal removal criteria, hopefully will make the decision process more objective and systematic.

CHAPTER II

DATA COLLECTION

REVIEW OF PUBLISHED LITERATURE

A review of available literature on the subject of traffic signal removal was undertaken to determine the existance and applicability of other proposed signal removal criteria, to determine applicable intersection parameters, and to identify government agencies that have removed traffic signals.

Signal Removal Criteria

There are currently no widely accepted criteria for removing existing traffic signals. The 1978 edition of the Manual on Uniform Traffic Control Devices(1) states that if the installation warrants are not met, a traffic signal should not continue in operation if already installed. The word "should" means that this is considered to be advisable criteria, recommended but not mandatory. As a point of contrast, the 1948 MUTCD required that:

> "When for a period of two or more consecutive hours the total vehicular volume entering an intersection having fixed-time signals installed under the warrant falls below 50 percent of the minimum volumes stated above for urban and rural intersections, flashing operation shall be substituted for fixed-time operation for the duration of such periods of reduced volume."

KLD Associates Inc. researched traffic signal warrants under NCHRP 3-20(2). The objective of the research was to evaluate the adequacy of the existing traffic signal warrants published in the MUTCD and the need for revised or additional warrants. The study recommended a downgrading warrant which is applicable at those signalized intersections where all of the following conditions are satisfied:

- None of the signal installation warrants are satisfied.
- Traffic signal was not installed under the Accident Experience Warrant.
- No hours of the recommended vehicular volume warrant are satisfied.
- Signal is not required in the judgement of the engineer.

KLD also recommended an interim period of 24 months prior to removing a signal during which time the signal is to operate in a flashing mode and the accident experience monitored.

The recommended downgrading warrant was developed by KLD in response to the returns of a survey of current traffic engineering practices. The survey consisted of a questionnaire mailed nationwide to states, counties and municipalities. Approximately 70 percent of the jurisdictions responding to the survey concurred that warrants are required for the purpose of downgrading existing signal installations. The survey questionnaires were reviewed by the research team for application to this project and were useful in identifying government agencies that had removed traffic signals.

Studies on Signal Removal

Very little research was available on the impacts of removing traffic signals and replacing them with stop sign control. One study(3) reported a general decrease in accidents after signals were removed at five low volume intersections of simple geometric design in Terre Haute, Indiana. Although no removal criteria were suggested, the use of some form of interim control period and/or driver notification process was recommended.

Another study(4) examined the before and after effects of the removal of a signal in Albany, New York on accidents, delay and fuel consumption. The signal was not justified under the MUTCD signal installation warrants. After removal of the signal, there was a significant decrease in accidents and improvement in traffic flow. The evaluation showed that the removal resulted in over two million fewer vehicle stops per year and almost 52,000 hours/year of reduced vehicle idling time to major street vehicles. This resulted in an estimated annual savings of 51,855 gallons of gasoline

Other Studies

Research on signal installation warrants was reviewed to determine parameters that should be considered in the development of signal removal criteria. As has already been discussed, KLD & Associates (NCHRP 3-20) developed new warrants and modified some of the existing ones.

The engineering data required to determine the necessity for a signal installation under warrants proposed by KLD, include hourly volume counts for each intersection approach, turning movement counts, pedestrian volume counts, 85-percentile speed of free-flowing vehicular traffic on the major street, physical layout of the intersection, and accident experience by type, direction, and severity for a period of a least two years.

A study by Paul Box(5) consisted of the collection of available information and data on intersection traffic volumes, vehicle headways, gaps in traffic streams, gap acceptance and rejection, delay, accidents, and other factors which should be considered in establishing warrants for traffic control signals. His report to the National Joint Committee also included the following suggested warrants: peak hour delay warrant, systems warrant and a pedestrian warrant.

Numerous studies (References 6-20) of the relationship between the installation of new traffic signals and intersection accidents were reviewed to determine what traffic and physical conditions tend to be unfavorable for an improved accident experience after signalization. This was done on the assumption that these same conditions might indicate a decrease in intersection accidents in the case of signal removal. The overall results of these studies varied considerably and were often contradictory. In some studies the total number of accidents decreased, while in others, an increase in total accidents after signalization was reported. Nevertheless, the data from this research did support some general conclusions which are discussed in a subsequent section.

A variety of literature concerning traffic operations at intersections under various types of intersection controls (References 2, 5, 20-22) were reviewed to develop techniques for estimating the changes in delay, stops and excess fuel consumption following the removal of a traffic signal. A number of local traffic engineering departments were contacted and several reports (References 2, 22, 23-25) were reviewed in determining the impact of signal removal on jurisdiction-related costs such as signal operation and maintenance.

SELECTION OF STUDY LOCATIONS

The initial task in collecting the extensive data base required to develop the criteria was to identify those political jurisdictions throughout the country that had recently removed traffic signals and to determine the availability of the desired data. The study contract required that 30 or more political entities which had removed traffic studies be selected and then visited for purposes of collecting pertinent information on the unique experience with the removal of traffic signals. In addition, the jurisdictions were to be selected in order to provide a good geographical cross-section of urban areas and governmental agencies which include city, county, and state representatives.

Study Location Review

An initial list of potential study locations was developed by reviewing the questionnaires used by KLD Associates during their research on traffic signal warrants (NCHRP Project 3-20). In particular, the question of the survey which covered the number of existing signal installations annually downgraded to sign or no control was analyzed and seventy-five jurisdictions were identified that had removed traffic signals.

The information contained in the NCHRP 3-20 questionnaires was six years old and there was nothing in the KLD survey results concerning the general nature of the signal removals nor on the availability of accident and traffic data. In light of these drawbacks, it was necessary to review the data with jurisdictions on the intial list by telephone and to determine their recent experience with traffic signal removal as well as the availability of before and after data at those intersections where signals had been removed. A number of jurisdictions not on the initial list were also contacted to provide a better geographic and demographic distribution and because it was known from other sources that particular jurisdictions had recently removed traffic signals.

In all, over 100 political entities in 41 states were contacted during the data review. Most of the jurisdictions reviewed were cities, although 26 state DOT/Highway Departments and approximately 5 county governments were contacted as well. The purpose of the data review and the general objective of the study was first explained to each state/county/city traffic engineer or an appropriate assistant. Each traffic engineer was then asked to update the data to indicate if any signals had been removed and replaced with stop signs or flashers in their jurisdiction during the recent past (3-5 years).Those that provided affirmative data were then asked approximately how many, the extent and availability of before and after data, and the general reason for the signal removals (e.g. unwarranted, closing of nearby major traffic generation, opening of new parallel highway, etc.).

Fifty-three jurisdictions, or just slightly over half of those contacted, had removed at least one signal in the last few years. The actual number of signals removed as well as the reason for their removal varied from jurisdiction to jurisdiction. For example, one city had removed only one signal in ten years and that was a school crossing signal (having two lenses in each face and operating only a few hours a day) which was removed after the adjacent school had been closed. On the other hand, a number of jurisdictions, such as Philadelphia, Pennsylvania; Columbus, Ohio; Kansas City, Missouri; Houston, Texas; and Milwaukee, Wisconsin, have had an active signal removal program ongoing for several years - removing signals at 5 to 10 intersections annually.

From the results of the KLD survey and telephone data review, it appears that the practice of signal removal is most prevalent in the midwest and southern states, particularly in older established cities. In the western portion of the country, signal removal is not very common although some of the large metropolitan areas have removed a significant number of signals in the last few years. Signal removal in the northeast is almost non-existent except for locations in the State of New York.

It should be noted that while a large number of States indicated on the KLD questionnaire of the existance of an annual signal downgrading program, the results of the telephone data review indicated that many of these states had been removing signals at a significantly lower rate or not at all during the last few years. An explanation of this is the fact that in most of the States reviewed, signal removal occurred at locations on rural routes after a parallel interstate route had opened thereby drastically altering the travel patterns on the rural route. Six to ten years ago, segments of the interstate system were opening at a rapid pace. Since then, however, new freeway construction has dropped thereby eliminating the conditions under which many States had been removing signals.

Selection of the 30 Jurisdictions

As previously stated, 30 study jurisdictions were to be selected and visitied for the purpose of requesting written documents and records pertaining to the removal of traffic signals. It was necessary to reduce the number of study locations to keep transportation costs as low as possible yet still maintain a data base of sufficient size. To accomplish this, those locations meeting both of the following criteria were chosen as recommended study sites:

- Five or more intersections where signals were removed.
- Adequate data available and obtainable.

A few locations that had removed signals at less than five intersections were also included because of their close proximity to another study location that met both of the criteria.

ACQUISITION AND SUMMARY OF INFORMATION

The traffic engineers for each of the selected jurisdictions were contacted by phone and arrangements were made for a member of the research project team to visit each one. Each of the phone calls was confirmed with a letter which included a list of the information and data that was being requested. The information included on this list (Table 1) is quite extensive. It was not expected, however, that any of the jurisdictions would have all of this information available. The primary purpose of such a comprehensive list was to identify all of the various information that was desired and thus enable the research team to collect any and all pertinent data which was available in the local traffic engineering files.

During a three month period in early 1979, the thirty-one (31) political entities shown in Figure 1 were visited. This included traffic engineering units of four state departments of transportation: Alabama, Louisiana, North Carolina, and Ohio. A demographic analysis of the sites visited is provided in Table 2.

The purpose of these visits was threefold:

- Collect written documents and records pertaining to the removal of traffic signals at intersections in each jurisdiction;
- Meet with the local traffic engineers and their staffs and determine the rationale and local procedures utilized to remove traffic signals. Also discuss institutional, political and legal implications;
- Field check and photograph as many of the study intersections as possible in order to obtain additional information that might not be available in the traffic engineering department's files.

Table 1. Requested Information

Individual Intersection Characteristics (for each intersection where signal was removed or attempt was made to remove signal)

- Physical geometrics (turning radii, sight distances, one-way operation, pavement markings, parking)
- Surrounding Land Use (residential, retail, industrial)
- Special Considerations (distance to nearest school, park, church)
- Locations of nearby signals
- Signal Layout (number of signal heads, displays)
- Phasing
- Type of Control (pre-timed, actuated, interconnect)
- Approach Speeds
- Traffic Volume (both before and after removal, turning movements, new nearby generators)
- Pedestrian Volume
- Accident Experience (<u>before</u> and <u>after</u> removal, accident reports, collision diagrams)
- Other (significant effects at nearby intersections)

Procedural Information (for each intersection)

- Initial signal installation (warrants cited, political considerations)
- Justification presented for removing traffic signals
- Concerns expressed by government body and other agencies
- Opposition (type and make-up of opposition groups, arguments and concerns, tactics)
- Type of control installation to replace signal (2-way or multi-way stop signs or flashing beacon)
- Overriding factor for retaining signal (if signal not removed)
- Public notification used before signal removed (newspapers, public relations)
- Interim adjustment period (signal put on flash, how long)
- Liabilities and legal problems after removal

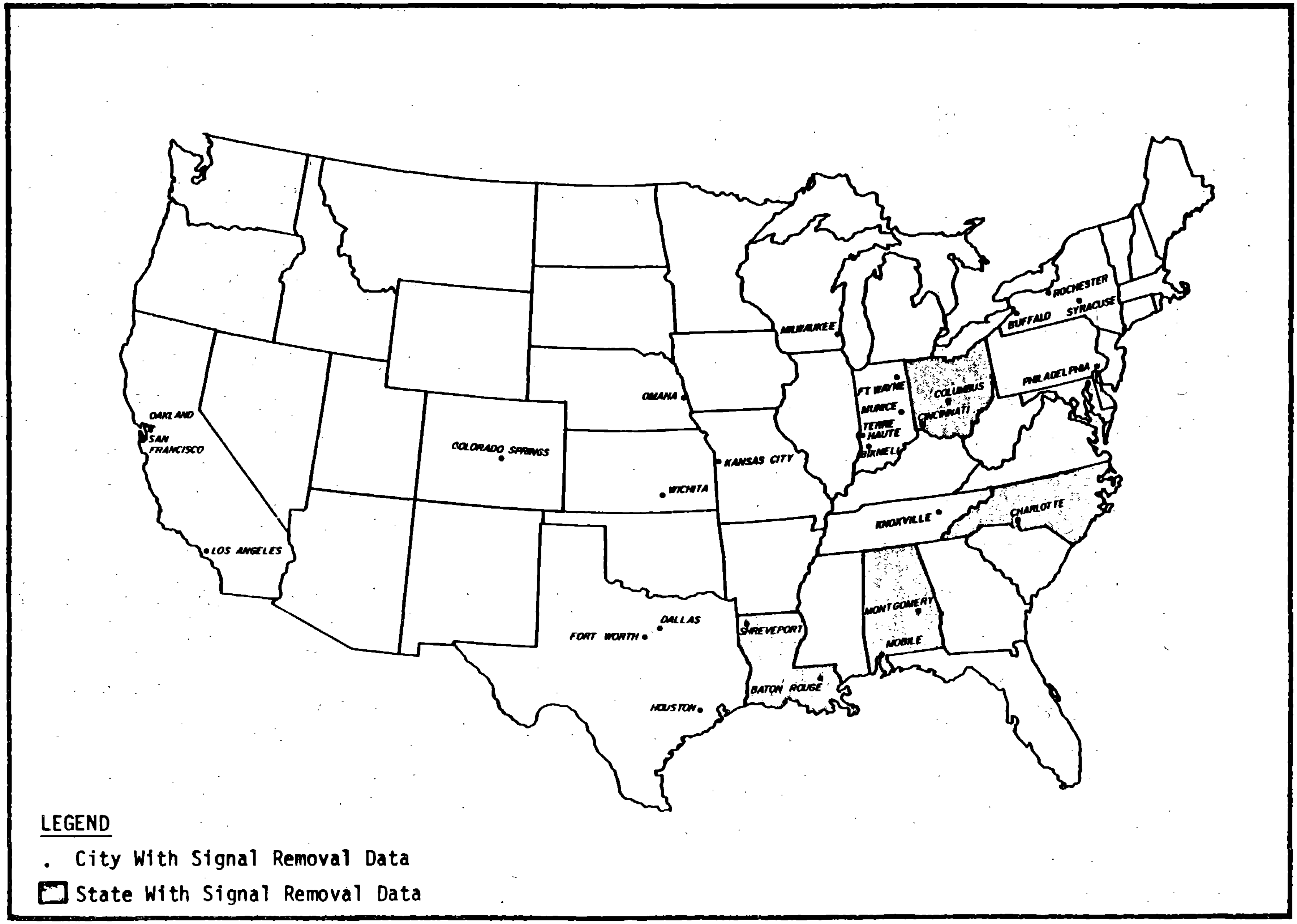

Figure 1. Study Locations

TABLE 2. DEMOGRAPHIC ANALYSIS OF STUDY LOCATIONS

JURISDICTION TYPE	POPULATION RANGE	NO. OF LOCATIONS
Cities/Counties	< 50,000	1
	50,000 - 100,000	2
	100,000 - 400,000	14
	400,000 - 700,000	5
	700,000 - 1,000,000	1
	1,000,000 +	4
States	-	4
TOTAL	-	31

Prior to beginning the extensive traveling required to assemble the signal removal data base, there was some concern as to the quantity and quality of information that would be available from the participating agencies. As it turned out, however, this was not a major problem. Not only were all the jurisdictions visited very cooperative, but most of them had available, as a minimum, volume data and before and after accident data for one year on at least three intersections where signals had been removed. Several of these locations, including Houston, Texas; Kansas City, Missouri; Milwaukee, Wisconsin; Philadelphia, Pennsylvania; and Buffalo, New York, had adequate information available on twenty or more intersections. Additional data on such items as type of signal control, distance to nearest signal, and intersection geometrics was available from a majority of the participating agencies. The data acquired from the traffic engineering files was supplemented by field investigations at a number of the intersections. Information obtained from these field investigations included additional data on intersection geometrics, lane configuration, surrounding land use, and side street sight distance. No before and after data on intersection stops and delays was available.

As one would expect, the raw data from each of the study locations varied as to the form in which it was received. For example, accident information included simple tables with just yearly totals for the intersections, computerized accident reports detailed collision diagrams, and even police accident reports. Some jurisdictions had traffic counts for only the AM and PM peak hour while others had 24 hour machine counts and 12 hour manual turning counts.

In all, enough data and information were collected during the data acquisition stage of the project to create the following data base:

- 227 intersections where signals were successfully removed.
- 42 intersections where signal removal attempts failed.

The various data and information available on each of these intersections were then summarized on a separate form in order to simplify the analysis of the data. A form, which is included in Appendix A, was filled out for each intersection.

CHAPTER III

SIGNAL REMOVAL PROCESS CHARACTERISTICS

As was mentioned in the previous chapter, one of the purposes of the site visits was to obtain information on the signal removal procedures utilized in each location. This includes such process characteristics as identification of candidate locations, removal criteria, removal authority, interim adjustment period control, public notification, and legal problems after removal. The findings of this element of the study are discussed below.

SIGNAL REMOVAL PROGRAMS

Of the 31 jurisdictions visited, five had an ~~active~~ signal removal program. All five of these jurisdictions are large metropolitan areas and have been actively searching for unwarranted signal installations for a number of years - removing an average of five to ten signals each year.

A few of the political entities, including some States, had short-term signal removal programs lasting a year or two at the most. These short-term programs were implemented for a variety of reasons including energy conservation, financial constraints, and implementation of a computer-based signal system. The most notable example of a short-term program is Buffalo, New York where nearlv 100 signals were removed in 1976 as a cost reduction measure.

Most of the study locations have handled signal removal on a case-by-case basis - removing or attempting removal of an unwarranted signal installation as a particular situation arises. Examples of some of these conditions are listed below:

- Closing of major traffic generators such as large business establishments, recreational areas, schools
- Disruption of street continuity due to urban development or interstate construction thus changing traffic flow patterns
- New interstates or improvement of alternative routes siphoning traffic away from intersection
- Change in street patterns (two-way operation to one-way operation)
- Anticipated freeway volumes never materializing
- Signal removed instead of being modernized to current design standards
- Construction of pedestrian overpass
- Repeated vandalism or maintenance problems

- Removal of temporary signal originally installed for construction detour
- Removal requested by police (in one city, police requested removal of a signal because at night, occupants of vehicles stopped at the signal were being robbed).

CANDIDATE LOCATIONS

In almost all of the jurisdictions visited, the identification of candidate locations for signal removal was an intuitive process. The local traffic engineering staff determined which signals should be considered for removal and additional analysis based on their personal knowledge and/or observation of the general conditions that existed at or near a particular intersection. Formal quanititative processes for identifying candidate locations were not used.

A few jurisdictions had used the findings of areawide traffic engineering studies (e.g., TOPICS Study) to identify candidate locations in addition to personal knowledge. Only three cities had a continuous program for reviewing and evaluating all signalized intersections with regard to the installation warrants. The programs generally consisted of taking volume counts at all signalized intersections on a periodic basis and comparing the intersection volumes to the installation warrants. Because of manpower and financial constraints, such counting programs have often fallen behind schedule and these jurisdictions have also used subjective observations to identify candidate locations.

SIGNAL REMOVAL CRITERIA

All the study locations used the MUTCD volume warrants as a basis for their removal criteria. While not part of a formal policy on signal removal, almost all the traffic engineers did state that the intersection volumes must be "substantially" below the warrants before removal of the signal would be attempted. In practice, this means that signal removal is not attempted in most jurisdictions if the intersection volumes exceed the volume warrant values for more than one or two hours. Two cities did have guidelines whereby a signal was designated as unwarranted if the intersection volumes did not satisfy a percentage of the MUTCD volume requirements for at least eight hours. One city used an arbitrary value of 75 percent. The other city, based on the assumption that five or more correctable accidents would occur each year with stop sign control, used an 80 percent value. (The MUTCD Accident Experience Warrant requires that there exist a vehicular volume not less than 80 percent of the requirements specified in the Volume Warrants).

In addition to intersection volumes, several jurisdictions used other factors as signal removal criteria which are listed below:

- School Crossing - If the signal is at an established school crossing or even near a school, removal of the signal is not attempted due to the politically sensitive nature of such an action. (It should be noted that a few cities have had some success with removing traffic signals near schools. In all, eight intersections in the data set of successful signal removals were adjacent to schools.)

- Progressive Movement - If the signal does not adversely affect signal coordination, removal may not be attempted. On the other hand, if the traffic signal causes poor signal spacing, removal may be agressively pursued.

- Sight Distance - One jurisdiction's policy was to not remove a signal if the intersection sight distance was less than the recommended minimum specified in the Transportation and Traffic Engineering Handbook (26). While other jurisdictions had no formal policy, it should be noted that the removal of signals at intersections with poor sight distance was encountered infrequently.

- Engineering Judgement - As has already been discussed, this involves intuition and general knowledge of the conditions, both present and future, that exist at the intersection. Political judgement is also very important. There are existing traffic signals that, regardless of how unnecessary and unwarranted they may be, have no chance of being removed due to institutional and political constraints.

SIGNAL REMOVAL AUTHORITY

In approximately two-thirds of the political entities visited, the authority to remove a traffic signal rests within the jurisdiction's traffic engineering or transportation department. In most of the other jurisdictions, removal of a traffic signal had to be approved by the City Council or a similar legislative body. The authority to remove a signal in three cities was vested in an independent committee or the city manager. In one of these cities, this committee was a Traffic Control Board which consisted of the traffic engineer, city engineer, and representatives from the police department, legal department, and department of community development. A unanimous vote was required to authorize the removal of a signal.

There appeared to be no correlation between the success of a signal removal program and the type of authorization required. For example, in some of the cities that have the most successful signal removal programs, City Council approval is required prior to the removal of a signal.

INTERIM CONTROL

All the jurisdictions visited, except for two, used some sort of interim control measure prior to the signal hardware being removed. The purpose of the interim control period is to allow drivers to adjust to the new intersection control. It also provides time to see if there are any complaints and to gauge the relative strength and validity of any opposition. Two forms of interim control measures were identified - bagging the signal heads and placing the signals in the flash mode.

- Bagging - Three cities used this interim control measure with stop signs being installed on the intersection approaches at the same time the signal heads were bagged. The signals remained bagged for periods ranging from one month to six months.

- Flashing - Placing the signals in the flashing mode was the predominant method of interim control. Signals that were converted to two-way stop control were flashed red-yellow, while signals at those intersections changed to multi-way stops were flashed red-red. Almost all of study locations that used this interim control measure flashed the signals for at least 30 days. Some jurisdictions flashed the signals for even a longer period. Three locations flashed signals for three months while three other locations left the signals on flash for six months. One city initially flashed the signals except during the peak hours and then later put the signals on 24-hour flash. Only three jurisdictions used this interim control measure for a period of less than one month.

NOTIFICATION

In general, most jurisdictions have provided very little notification of the plans to remove a traffic signal. In a number of cities, the traffic engineer has informed the police department as a matter of courtesy. In several of those cities where city council approval is not required, the council or the appropriate councilperson is often notified of the proposed signal removal and the subject is discussed so the councilperson can answer to the constituency in the event of complaints.

In those locations where city council approval of signal removal is required, the council meetings do get coverage in the local newspapers. In this way, some notification is provided to the general public. Nevertheless, in general, signal removal is a low keyed process and public notification is very limited. In three jurisdictions, the date that the interim control is to be implemented and the general reasons for the signal removal are published in the newspaper. A press release from the City of Omaha, Nebraska is provided as Appendix D. Another three cities have made a practice of contacting the surrounding residents and business establishments, either by phone or by letter.

The most effective means of public notification, in terms of coverage and ensuring that the public is made aware of the proposed removal, was found in Colorado Springs, Colorado. During the 30 day period when the signal is in flashing mode, a sign is posted on all intersection approaches stating that the signal is to be removed and the date it is to be removed. An example of the sign is shown in Figure 2.

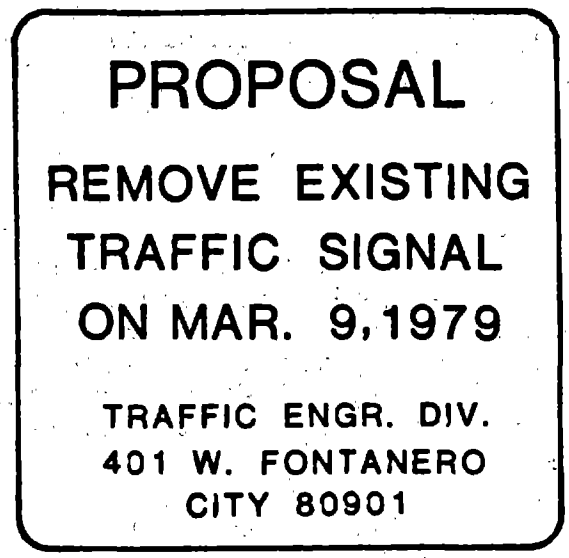

FIGURE 2. SIGNAL REMOVAL SIGN - COLORADO SPRINGS

SIGNAL REMOVAL STRATEGIES

The removal of a traffic signal is often a political and institutional decision as much as it is a technical decision. There are certain strategies that can be very useful in increasing the chances of a signal removal attempt being successful. During the study location visits, several strategies were identified which are discussed below.

Facing the Opposition

Opposition to a proposed signal removal is often a very emotional situation in which technical and logical explanations are useless. In one city, when there is a large amount of opposition to a proposed removal, the traffic engineer or one of his assistants meets with representatives of the opposition at the intersection during the peak hour to show and to explain to them that there is no traffic problem when a signal is not operating at the intersection. (The signal is in the interim control mode at the time.)

Opportunity

Some jurisdictions have been very opportunistic about signal removal. For example, in one city, signals that were disabled due to vandalism or a traffic accident were simply removed instead of being repaired or replaced. In another city, signal installations have been removed while one of the intersecting streets has been closed for repair. After completion of the construction, however, the signal has not been reinstalled and, in general, people have not been concerned that a traffic signal had existed there before.

Timing

Several traffic engineers of cities where city council approval is required stated that they never bring a signal removal proposal before the council during the members' campaigns for re-election. With the removal of a signal being such a visible item and often politically sensitive, the chances of having the proposed signal removal approved by the council are at their lowest just prior to election time.

In a northern city, signals are not removed during the winter since snow drifts may reduce the side-street sight distance during the first critical months of driver adjustment to stop control. The reduced sight distance may cause an increase in the first months following signal removal, thereby forcing reinstallation of the signal.

Relocation

This strategy has been used by a few of the study locations with great success. The unwarranted signal is "relocated" to another, near-by intersection which will benefit from signalization or at least where the negative aspects of signal control are not as great. While the signal hardware is not physically relocated, by placing the unwarranted signal in the interim control mode at the same time the new signal installation is turned on, a signal can be removed under conditions (such as public opposition and politics) that otherwise might make removal impossible. The following two case studies demonstrate how effective this strategy can be.

Oakland, California - MacArthur Blvd. at Randolph Ave.

Due to the opening of the MacArthur Freeway in 1965, the pre-timed traffic signal at the intersection of MacArthur Blvd. and Randolph Avenue was no longer warranted. The traffic crossing MacArthur Blvd. at this intersection was practically non-existent (300-400 vpd) since Randolph had been dead-ended by the Freeway approximately 150' beyond the intersection. In addition, the traffic volume on MacArthur, having been converted to a local traffic carrier, had been reduced from 19,000 to 5,000 vpd. Thus, the City Traffic Engineer initiated the removal procedures by sending a letter to the residents and businesses in the area stating that the signal was going to be removed.

The response to the proposed removal was quite large and mostly negative. A number of letters were sent to the traffic engineering department, a petition was submitted and many phone calls were received opposing the removal of the signal. A sampling of some of the comments that were made include:

- "removal would be against the well being and safety of all concerned"
- "danger to children"
- "fear that bus stop will be removed if signal removed"
- "street will become a race track"
- "deep concern for elderly people who live on the block"
- "bound to be accidents if signal is removed"

Despite all these complaints, the signal was put on flashing operation on January 31, 1966. This action caused another petition, more complaints and even some threats such as:

- "I am going to talk to my councilman"
- "number of deaths will occur"
- "if I get killed, (my) heirs will sue the City"

The signal remained on flash until the next Oakland City Council meeting on February 15, 1966 when the Council decided to retain the signal.

Another attempt to remove the signal was made in 1971, but this time the strategy of relocation was used. It was proposed that the signal be relocated one block to the intersection of MacArthur and Ardley Avenue. In June, another letter was sent to the residents and merchants in the area. This time, 13 written responses to the letter were received - 10 in favor of the relocation with comments such as:

- "poor planning - should have been done by 1965"
- "excellent idea"
- "very good and timely"

On September 7, 1971, the Oakland City council approved the relocation and the signal at MacArthur Blvd. and Randolph Avenue was finally removed.

The signal at MacArthur and Ardley was not warranted either. Obviously, the optimum action would have been to remove the signal at Randolph Avenue and not signalize the intersection at Ardley Ave. As was just described, this was tried and was politically impossible. The intersection of Ardley and MacArthur was the only intersection in the immediate area that was even close to satisfying the signal warrants (the volumes did satisfy the MUTCD Volume Warrant for two hours and Ardley is a through street with an overpass over the MacArthur Freeway). While having a signal at this intersection may be the better of two bad situations, the negative impacts of signal control are much less than if the signal had remained at the Randolph intersection.

Cincinnati, Ohio - Clifton Ave. and University Ave.

Clifton is a major street that goes through the University of Cincinnati. University Avenue was closed to through traffic but was still used as a crosswalk for pedestrians, although not enough to warrant a signal. During the peak hour, 140 pedestrians crossed the major street and the volume on University Ave. was approximately 1800 vph. The signal was poorly located with respect to progressive movement on Clifton Avenue.

The signal was put on flash in June, 1973 with the intention of installing a new midblock signal at another near-by location on Clifton Avenue. This new crosswalk location not only served four times the number of pedestrians, but was superior with respect to progressive movement on Clifton as well. Even after a pedestrian fatality occurred at the intersection of Clifton and University while the signal was still on flash in November 1973, the University of Cincinnati indicated no objection to the proposed "relocation". (Note - The pedestrian involved in the fatal accident was not in the crosswalk and was cited by the police while the driver of the vehicle was not). Nevertheless, it is still somewhat astonishing that the signal was removed with the concurrence of the University and the City Council even after a fatal accident had occurred there. The signal was removed at Clifton and University when the new cross walk location was signalized. The crosswalk at University and Clifton was retained and was illuminated with spotlights.

The use of this strategy is dependent on there being an unsignalized intersection in the immediate area (one or two blocks at most) that is more suitable for signalization than the one planned for signal removal. The strategy of "relocation" does not decrease the number of signalized intersections and is thus not recommended as a general practice. However, under the right circumstances and when severe political constraints exist, it can be very effective.

LEGAL REPERCUSSIONS

None of the jurisdictions visited have had any legal repercussions or law suits arising out of signal removal.

CHAPTER IV

CHARACTERISTICS OF SIGNAL REMOVAL DATA BASE

The information from the 31 study locations on signal removal experience was summarized and statistics characterizing various intersection descriptors were prepared. The intersection descriptors included variables which depict the physical and geometric features, traffic flow characteristics, accident experience, site location, traffic signal design and operation characteristics of the intersections where signals have been successfully removed.

The data set involving successful signal removals was divided into the following categories:

- Rural Intersections - 10 locations
- Urban Intersections - 217 locations.

The characteristics of each data set are discussed separately.

RURAL INTERSECTIONS

The data set for rural intersections is unfortunately quite small. The reason for this, however, is not due to a lack of signal removal practice in rural areas. From the NCHRP 3-20 questionnaires and the telephone contacts made as part of the study location review, it is quite obvious that several states have removed numerous signals during the last decade.* A number of these removals were in conjunction with the opening of segments of the Interstate Highway System and the resulting siphoning of traffic off of the major rural routes.

The problem was the availability of adequate data on these rural intersections. For example, the State of Alabama removed between 70-100 unwarranted signals in the early 70's as part of a state-wide signal upgrading program. However, because of the period of time that has elapsed since their removal, no data were available. Similarly, North Carolina has removed nearly 50 signals in the last 10-12 years. Very few of these were removed in the last 3-5 years for which data were available.

The ten intersections in this data set were located in or near small towns having a population of less than 20,000. Half of these signalized rural intersections were maintained by State DOT's. Of the ten locations, five were converted to two-way stop control, while the other five were changed to all-way stop control None of the intersections satisfied the current MUTCD warrants (70 percent values) during any hours except one

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* The results of the KLD questionnaires indicate that during the early 1970's, states were removing an average of 2.5 signals/year.

location which exceeded the warrant values for only one hour. The speed limit at those locations downgraded to an all-way stop was less than 40 miles per hour. The speed limit at two of the locations converted to a two-way stop was greater than 40 miles per hour.

URBAN INTERSECTIONS

The large size and quality of the data set for urban intersections made it possible to determine the distribution of a number of intersection descriptors and thus, identify the general characteristics of those intersections in urban areas where signals have been successfully removed.

Physical and Geometric Features

Table 3 summarizes the physical and geometric features of the urban intersections where signals were successfully removed. It is evident that the geometrics of these intersections is relatively simple: three or four approaches with usually no more than one or two lanes in each direction, streets crossing at right angles, and no offset between opposite approaches.

Land-Use Characteristics

The distribution of the surrounding land use at urban intersections where signals were removed is shown in Table 4. Of the ten intersections classified as "other", eight were located within one block of an active school.

Operational Characteristics

Table 5 summarizes the signal operation and design characteristics of the urban intersections where signals were removed. At nearly three-fourths of the urban intersections, the signal layout conformed with the design standards contained in the MUTCD. The great majority (77 percent) of the signal installations downgraded to stop sign control operated with fixed-time controllers. This is slightly higher than the proportion of all urban signal installations utilizing pre-timed controllers (71 percent).*
Similarly, the percentage of removed signals that operated with two phases (91 percent) is slightly higher than the percentage of all urban signals utilizing two phase operation (86 percent).

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* This figure was obtained from the results of the KLD questionnaires which were received from 135 cities throughout the country.

Table 3. Physical/Geometric Characteristics of Urban Intersections (Signals Removed)

Number of Approach Legs	Number of Intersections
3	75 (34%)
4	149 (65%)
5	2 (1%)
Offset Approaches	**Number of Intersections**
Yes	10 (6%)
No	165 (94%)
Angle of Crossing	**Number of Intersections**
90°	141 (81%)
75°-90°	14 (8%)
60°-75°	10 (6%)
45°-60°	10 (6%)
Major Street Type	**Number of Intersections**
One-way	34 (16%)
Two-way, undivided	162 (77%)
Two-way, divided	14 (7%)

NOTE - Total number of intersections for each condition description varies depending on the availability of information.

Table 4. Land-Use Characteristics of Urban Intersections (Signals Removed)

Surrounding Land Use	Number of Intersections
Residential	38 (26%)
Commercial	49 (34%)
Mixed (Res./Comm.)	29 (20%)
Industrial	19 (13%)
Other	10 (7%)

Table 5. Operational Characteristics of Urban Intersections (Signals Removed)

Signal Operation	Number of Intersections
Fixed Time	99 (77%)
Actuated	30 (23%)
Signal Design	**Number of Intersections**
MUTCD Conformity	102 (74%)
MUTCD Non-Conformity	35 (26%)
Number of Phases	**Number of Intersections**
2	118 (91%)
3+	11 (9%)

Traffic Volume Characteristics

Table 6 summarizes the traffic volume characteristics of the urban intersections where traffic signals were removed. As would be expected at an intersection where a signal has been replaced with stop signs, the traffic volumes are relatively low. The highest volume intersection in the study had a peak hour entering volume of just over 3,000 vehicles (the side street traffic accounted for less than two percent of this total, thus the signal was not warranted).

Another method used to analyze the volume characteristics of the urban intersection data set was to examine the number of hours the traffic volumes at each intersection satisfied the current MUTCD vehicle volume warrants. Warrant #1 is the Minimum Volume Warrant and Warrant #2 is for the Interruption of Continuous Flow. Of the 208 intersections for which it was possible to determine the number of hours a signal was warranted, only 24, or 11 percent of the sample, satisfied Warrant # 1 during any hours of the day at all. At most of these locations the volume equalled or exceeded the warrant values for one to two hours. Only two intersections in the study satisfied Warrant #1 for five or more hours.

A larger number of intersections did meet for at least one hour the minimum values of Warrant #2 (23 percent). Nevertheless, it is quite obvious that at the great majority of intersections where signals have been removed, traffic conditions have not satisfied the MUTCD volume warrants during any hours of the day. These results verify what was discussed in the previous chapter on signal removal process characteristics - that it is the practice of most traffic engineers not to attempt removal of an existing traffic signal unless it is "substantially" unwarranted.

Pedestrian counts were available for only a few of the study locations. With the exception of one location, the number of pedestrians crossing the major street was quite low- an average of 14.1 pedestrians during the peak hour (not counting the above mentioned intersection). The pedestrian activity at the other study locations for which pedestrian counts were not available was described as "little" or "non-existent" by the local traffic engineers. As mentioned, one intersection, the Cincinnati case study on the strategy of relocation,did have substantial pedestrian activity - 140 pedestrians crossing the major street during the peak pedestrian hour. Nevertheless, this intersection did not satisfy the MUTCD Pedestrian Crossing Warrant during any hours of the day as did none of the other study locations.

Table 6: Traffic Volume Characteristics of Urban Intersections (Signals Removed)

Peak Hour Entering Volume*	Number of Intersections
0-500	40 (18%)
500-900	78 (36%)
900-1300	54 (25%)
1300-1700	26 (12%)
1700+	19 (9%)
Number of Hours MUTCD Warrant #1 Satisfied	**Number of Intersections**
0	184 (89%)
1-2	15 (7%)
3-4	7 (3%)
5+	2 (1%)
Number of Hours MUTCD Warrant #2 Satisfied	**Number of Intersections**
0	160 (77%)
1-2	26 (13%)
3-4	11 (5%)
5-6	7 (3%)
7+	4 (2%)

*Sum of Major Street Volume and Higher Side Street Volume

Accident Experience

The "before" accident experience at the intersection in the urban data set is shown in Table 7. In addition to low volumes, intersections in urban areas were signals have been removed also tend to have a low accident frequency. The mean accident frequency prior to removal for the urban data set was 2.36 accidents/year. Over 60 percent of the intersections had an average annual accident frequency of two or less. The average accident frequency at individual intersections prior to signal removal ranges from zero accidents/year (which occurred at 16.3 percent of the intersections) to eighteen accidents/year at one of the study intersections.

TWO-WAY STOP vs. MULTI-WAY STOP

When a traffic signal is removed, it is necessary to install an alternate traffic control device - usually some form of stop sign control. The urban data set of urban intersections where signals were successfully removed was divided into the following groups and analyzed:

- Intersections converted to two-way stop -- 191 intersections.
- Intersections converted to multi-way stop -- 26 intersections.

As can be seen from the relative size of the two groups, most of the urban locations visited have primarily utilized the two-way stop sign arrangement at intersections after the removal of a signal. Two cities, Philadelphia, Pennsylvania and Terre Haute, Indiana, have replaced signals with multi-way stops at most of the removal locations in their jurisdictions.

There was no discernable differences between the two groups with regards to the geometric features, land use, and signal operation characteristics of the intersection. There are, however, some major differences in accident experience and traffic flow characteristics between the two groups which are summarized in Table 8.

As should be expected, the major street and side street traffic volumes are more balanced at those intersections converted to multi-way stop control than at the two-way stop controlled intersections. This is further indicated by the fact that at none of the 26 intersections converted to multi-way stop did traffic volumes at any time meet the minimum values of Warrant #2, the Interruption Warrant, which favors unbalanced flow conditions. The ratio of major street volume to total side street volume for the intersections converted to multi-way ranged from 1.1 to 4.6 with an average of 2.1.

Table 7. "Before" Accident Experience of Urban Intersections (Signals Removed)

Average Annual Accident Frequency	Percentage of Intersections
0	16.3%
0-1	22.8%
1-2	21.8%
2-3	12.1%
3-4	11.2%
4-5	7.0%
5-6	3.7%
6+	5.1%

Table 8. Traffic Flow Characteristics and Accident Experience at Signalized Urban Intersections Before Downgrading To Two-Way Or Multi-way Stop Control

Intersection Descriptor	Two-way Stop	Multi-way Stop
Mean Average Annual Accident Frequency	2.46	1.70
Mean Peak Hour Entering Volume*	980 vph	480 vph
Mean Average Entering Volume during 4 Peak Hours*	850 vph	420 vph
Percent of Intersections Satisfying MUTCD Warrant #1 for at Least One Hour	11.5%	12.5%
Percent of Intersections Satisfying MUTCD Warrant #2 for at Least One Hour	26.6%	0.0%
Mean Ratio: Major Street Volume/ Higher Side Street Volume (During 4 Peak Hours)	15.0	2.8

*Total Major Street Volume plus Higher Side Street Volume.

Only four intersections in this group actually satisfied the Multi-Way Stop Sign Warrant contained in the MUTCD.* In fact, over one-half of the intersections did not even meet one hour of the warrant. Nevertheless, these results do indicate that, in general, those cities included in the study are implementing multi-way stop control after signal removal at locations where it is beneficial, i.e. intersections with relatively low volumes and balanced traffic flows between the major street and side street.

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* a) The total vehicular volume entering the intersection from all the approaches must average at least 500 vehicles per hour for any eight hours of an average day; and

b) the combined vehicular and pedestrian volume from the minor street or highway must average at least 200 units per hour for the same eight hours.

CHAPTER V

ACCIDENT IMPACTS

This chapter of the report covers the investigation of the impacts of traffic signal removal on accidents. Data used in this analysis were obtained for the 227 case study intersections from across the country where signals have been removed.

OVERVIEW OF ACCIDENT IMPACTS

Table 9 summarizes the changes in average annual accident frequency per intersection following traffic signal removal.

Traffic volume data were not available for most intersections both before and after signal removal. Therefore traffic volume based accident rates were not analyzed. Where both before and after volume data were available, changes in volume levels were small and no upward or downward trends were apparent. Therefore, use of changes in average annual accident frequency per intersection should not differ greatly from an analysis of accident rates based on volume.

The data are divided into four basic subsets:

- Rural Intersection
  - Signal Replaced by Two-Way Stop
  - Signal Replaced by Multi-Way Stop
- Urban Intersection
  - Signal Replaced by Two-Way Stop
  - Signal Replaced by Multi-Way Stop

It should be noted that the category "two-way stop" is synonymous with "minor-road stop". In some cases minor roads are either one-way or terminate at a T-intersection, thereby forming only one stop-controlled approach. The phrase two-way stop is used for simplicity.

Rural Intersections

The data base contained only 10 rural intersections for which accident data were available for the periods before and after signal removal. These were split evenly between conversions to two-way stop and multi-way stop.

Table 9. Summary of Accident Impacts of Signal Removal

	Rural Intersection Signal Replaced By		Urban Intersection Signal Replaced By	
	Two-Way Stop	Multi-Way Stop	Two-Way Stop	Multi-Way Stop
Number of Intersections in Sample	5	5	191	26
Total Accidents				
Average Annual Frequency per Intersection				
Before Signal Removal	4.83	0.53	2.46	1.70
After Signal Removal	8.60	0.60	2.38	0.68
Change	+3.77	+0.07	-0.08	-1.02
	Significant at $\alpha = .10$	Not Significant	Not Significant	Significant at $\alpha = .005$
Injury Accidents				
Average Annual Frequency per Intersection				
Before Signal Removal	0.88	0.07	0.70	0.50
After Signal Removal	3.17	0	0.63	0.19
Change	+2.29	-0.07	-0.07	-0.31
	Significant at $\alpha = .10$	Not Significant	Not Significant	Not Significant

NOTE: Statistical difference tests were performed using the paired comparison t test. See Appendix C for detailed discussion of methodology.

Two-Way Stop - Rural Intersections

For conversions to two-way stop control, the mean change in annual accident frequency following signal removal was an increase of 3.77 accidents per year, statistically significant change at α =0.10 The annual frequency of injury accidents also increased significantly by 2.19 accidents per year at these rural intersections after signals were replaced by two-way stops. There were no fatal accidents at these intersections.

It is important to note that, although the accident impact results for the sample of rural intersection conversions to two-way stop control showed significant accident increase, the sample (n = 5 intersections) is much too small to draw general conclusions. Nontheless, there is a concern that, other things such as traffic volume being equal, there is greater inherent risk in attempting to cross or enter a main rural road from a stop-controlled side road because higher speeds make gap acceptance judgements a more difficult task. Additionally, involvement of higher speed vehicles in collisions increases the risk of injuries. The data in this study tend to confirm the above hypotheses, but are not drawn from a sufficiently large cross-section of conditions for the results to be considered representative or generalizable.

Multi-Way Stop - Rural Intersections

For the five rural intersections in the data base where signals were replaced with multi-way stop control, average annual accident frequent changed by very small and statistically insignificant amounts following signal removal. No significant changes were found for either total intersection accidents or injury accidents. Once again, it should be noted that the sample of only five rural intersection conversions to multi-way stop was too small for the results to be representative or generalizable. One can hypothesize that multi-way stop reduces the risk of severe angle collisions and increases the risk of main road rear-end collisions. However, the sparse sample did not permit these hypotheses to be tested.

The reader should take care not to make a direct comparison of the relative risks of conversions to two-way versus conversions to multi-way stop control at rural intersections based on these research results. First, the samples are too small; and second, conditions at the two sets of intersections, particularly traffic volume levels, are not comparable.

Urban Intersections

The signal removal accident impact data base was much larger for urban intersections. Included were 191 intersections where signals were replaced by two-way stops and 26 intersections where conversions were made to multi-way stops.

Two-Way Stop

For the total set of conversions to two-way stop control, no statistically significant change occurred in average annual frequencies for either total accidents or injury accidents. (Note - Only one intersection experienced a fatal accident. This was included in the analysis as an injury accident.) Because of the relatively large sample size, however, these intersections were stratified with respect to key independent variables affecting accident outcome following signal removal. The results of this analysis are presented subsequently in this chapter.

Table 10 and Figure 3 presents the frequency distribution of changes in average annual accident frequency for individual urban intersections where signals were replaced by two-way stop control. The distribution is symmetrical and approximates the normal form. The change in average accident frequency after signal removal at individual intersections ranged from an increase of 7.1 accidents/year at one location to a reduction of 12.8 accidents per year at another.

While there was little change in overall accident frequency per urban intersection following conversion to two-way stop control, there was a shift in the types of collisions. This shift in collision type is illustrated in Table 11 which is based on data from 128 of the 191 urban intersections converted to two-way stops for which information on collision type were available. The results show that, following conversion from signal control to two way stop control, rear-end collisions tend to decrease whereas right-angle collisions tend to increase. This shift is the opposite of what generally happens after signals are installed. In case of this study's data the relative magnitude of these opposite shifts in collision types are approximately equal. Rear end collisions fell by 49 percent while right angle collisions rose by 51 percent. The data showed very little changes in turning, pedestrian and "other" accident categories following signal removal.

The literature, in general, shows somewhat higher rates of injury in right-angle collisions than in rear-end collisions. But in this study, the result of the shifts in collision type following signal replacement by stop control at urban intersections had no statistically significant effect on average annual frequency of injury accidents. These results suggest there is no need, at least at the urban intersections, to make a "trade off" analysis of the increase in right-angle collisions versus decreases in rear-end collisions following signal conversion to two-way stop.

Table 10. Distribution of Accident Impacts of Signal Removal, Replaced by Two-Way Stops, Urban Intersections.

CHANGE IN ANNUAL ACCIDENT FREQUENCY		NUMBER	PERCENT
INCREASE	3.5 or more	10	5.2
	2.5 to 3.5	8	4.2
	1.5 to 2.5	13	6.8
	.5 to 1.5	25	13.1
LITTLE CHANGE	.5 to +.5	59	30.9
DECREASE	−.5 to −1.5	31	16.2
	−1.5 to −2.5	25	13.1
	−2.5 to −3.5	13	6.8
	−3.5 or more	7	3.6

Table 11. Impact on Urban Signal Replacement by Two-Way Stop Control on Collision Types, Urban Intersections

	AVERAGE ANNUAL ACCIDENT FREQUENCY PER INTERSECTION		
COLLISION TYPE	BEFORE REMOVAL	AFTER REMOVAL	PERCENT CHANGE
Rear End	.864	.437	−49%: Significant
Right Angle	.90	1.36	+51%: Significant
Turning	.316	.314	Not Significant
Pedestrian	.141	.083	Not Significant
Other	.374	.356	Not Significant

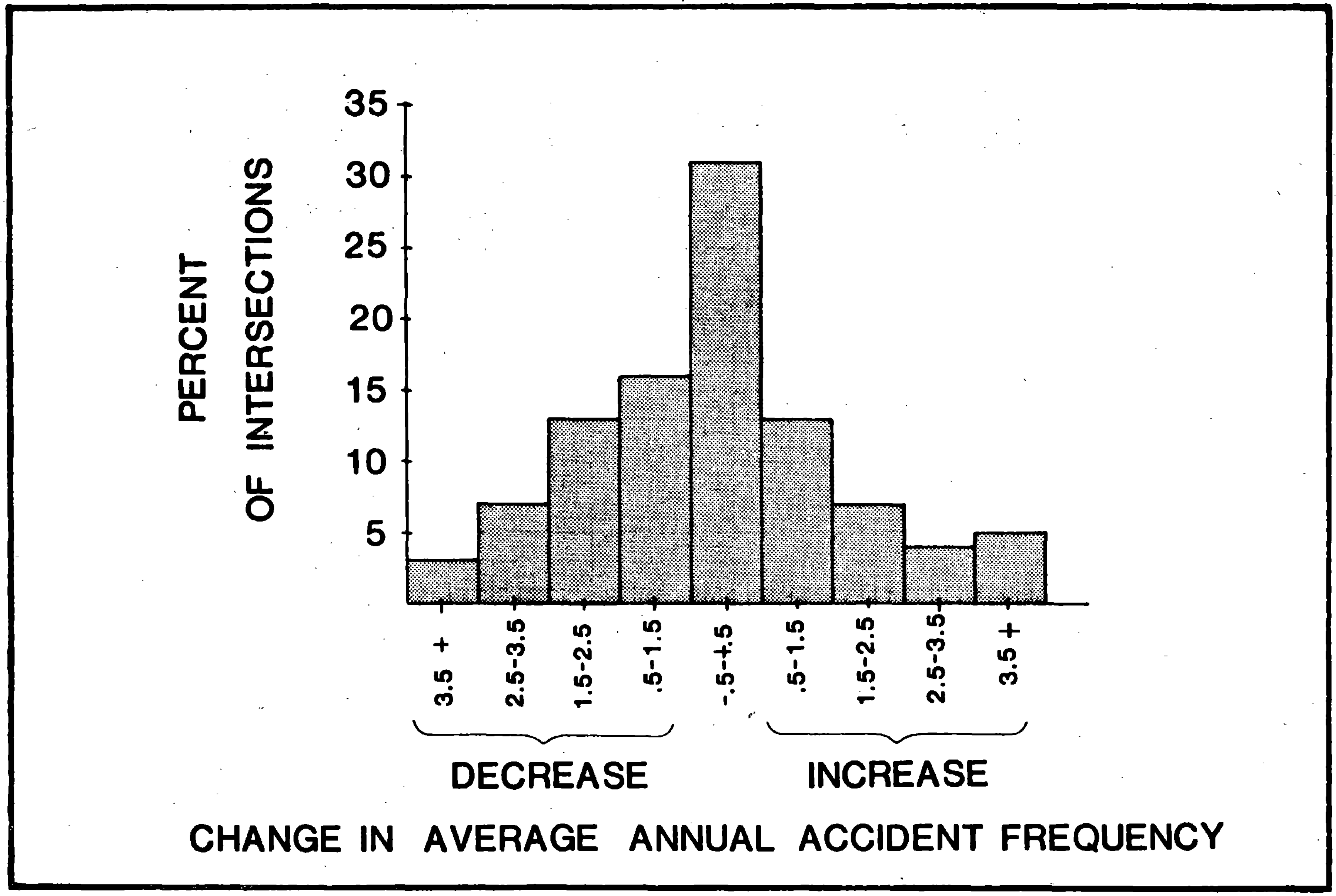


Figure 3. Distribution of Changes in Average Annual Accident Frequency Following Signal Removal and Installation of Two-Way Stop Control, Urban Intersections

Multi-Way Stop - For the urban intersections converted to multi-way stop control (see previous Table 9), there was a statistically significant decrease of 1.02 in average annual accident frequency per intersection following signal removal. Average annual injury frequency also decreased by 0.31 per intersection after signal removal but this change was not statistically significant.

Although the sample size for conversions to all-way stop (n = 26 intersections) is much smaller than for conversions to two-way stop (n = 191 intersections), these results are viewed as important. In general, it can be said that for intersections where signal control has been replaced with multi-way stop control, the average improvement in safety has been significant. (It must be emphasized that these are intersections with lower volumes and much smaller main road to side road volume ratios than the intersections converted to two-way stop).

This is clearly different from the finding of no significant change in average annual accident frequency at intersections converted from signals to two-way stops. But one should not directly compare either the absolute accident frequencies or the changes in accidents for the two cases. Intersections where signals were replaced by multi-way stops are not comparable to intersections where conversions were made to two-way stops.

FACTORS INFLUENCING ACCIDENT IMPACTS

From the results just presented, it is obvious that a simple signal/no signal dichotomy is inadequate to explain the difference in accident experience after signal removal at urban intersections which are converted to two-way stop control. There are other factors or intersection descriptors which contribute to the change in accident frequency after signal removal. The sample of urban intersection conversions from signal to two-way stop control was large enough, however, (n = 191 intersections) to permit a more detailed examination of intersection factors affecting accident outcome. This subset was stratified with respect to a variety of intersection design and traffic characteristics variables to determine if the accident outcome following signal removal was significantly dependent on any of these factors. This was done using two-way classification (or so-called contingency) tables in which each variable was arrayed against change in average annual accident frequency following signal removal. Tests of the significance of each variables' affect on accident outcome was tested using the Chi-square statistics. The results of this analysis are summarized in Table12. Detailed results are presented in Appendix B.

The results indicate that three variables had a significant effect upon the accident impact following signal removal and conversion to two-way stop control:

Table 12. Intersection Condition Descriptors and Their Influence on Accident Impacts.

Intersection Condition Descriptor	Results of Chi-Square Test
Number of Approaches	Not Significant
Angle of Crossing	Not Significant
# Lanes (Major St.)	Not Significant
# Lanes (Minor St.)	Not Significant
Side Street Sight Distance	Significant at α = .10
Major St. Operation (One way, two way)	Not Significant
Distance from Nearest Signal	Not Significant
Signal Design (Conformance to MUTCD)	Not Significant
Signal Operation (Pre-timed, actuated)	Not Significant
Entering Volume (Peak Hour)	Not Significant
Product (Major St. Volume X Minor St. Volume)	Not Significant
# Hours MUTCD Warrant 1 Satisfied	Not Significant
# Hours MUTDC Warrant 1 Satisfied (80% Values)	Not Significant
# Hours MUTCD Warrant 1 Satisfied (60% Values)	Significant at α = .10
# Hours MUTCD Warrant 2 Satisfied	Not Significant
"Before" Accident Frequency	Significant at α = .001
Right Angle Accident Frequency	Not Significant
Rear-End Accident Frequency	Not Significant

- Side-street sight distance as defined in the <u>Transportation and Traffic Engineering Handbook</u> (26).

- Intersection volume magnitude, as measured by the number of hours per day that volumes satisfy at least 60 percent of the MUTCD signal installation Warrant Number 1.

- Average annual frequency of total accidents per intersection with traffic signal control in effect, i.e. before signal removal.

Effect of Side-Street Sight Distance

The urban data set included 15 intersections with inadequate sight distance (i.e. less than 300 feet) for safe crossing or entering gap acceptance for main road speeds of 30 mph. All of these were intersections at which signals were replaced by two-way stop control. Ten of these 15 intersections had before and after data on injury accidents as well as total accidents.

The research results, summarized in Table 13, show that accidents increased significantly following conversion to two-way stop control at the poor sight-distance intersections. The frequency of total accidents increased by an average of 2.82 per year per intersection, while average annual injury accidents rose 0.61 per intersection. Twelve of the of 15 intersections experienced an increase in annual accident frequency.

As expected, the increase in total accident frequency was attributable mainly to higher incidence of right angle collisions. This is shown in Table 14. The frequency of right angle collisions increased by an average of 2.64 per intersection per year following conversion from signal to two-way stop control. None of the other collision types had statistically significant changes in annual frequency following signal removal.

Traffic Volume Magnitude and Accident Frequency Before Signal Removal

The other two variables which significantly influenced the accident impact of signal removal, as noted previoulsy, were:

Table 13. Accident Impacts at 15 Urban Intersections With Poor Sight Distance.

Annual Average Accident Frequency per Intersection	Total Accidents	Injury Accidents
Before Signal Removal	2.03	0.60
After Conversion to Two-Way Stop	4.85	1.21
Change	+2.82 (Significant at $\alpha = 0.005$)	+0.61 (Significant at $\alpha = 0.05$)

Table 14. Accident Impacts at 12 Urban Intersections With Poor Sight Distance, by Collision Type

Collision Type	Average Annual Accident Frequency per Intersection		
	Before Signal Removal	After Conversion To Two-Way Stop	Change
Right Angle	1.03	3.67	+2.64 (Significant at $\alpha = 0.005$)
Rear End	0.47	0.47	Not Significant
Turning	0.25	0.49	Not Significant
Pedestrian	0.12	0	Not Significant
Other	0.29	0.78	Not Significant

Note: Totals for "before and "after" accident frequency do not equal values in Table 13 since collision type data were available for only 12 of the 15 intersections with inadequate sight distance.

- Traffic volume magnitude, as measured by the number of hours per day the intersection traffic volumes equal or exceed 60 percent of the minimum volumes in MUTCD Warrant NO.1. Intersections with higher traffic volumes tended to have increased accident frequency, whereas one with lower volumes tended to have reduced accident frequency following signal removal.

- Average annual accident frequency before signal removal At intersections with very low "before" accident frequencies (less than 1 per year), signal removal tended to result in increased accidents. Conversely, accident reduction followed signal removal at intersections with higher before accident frequencies i.e. more than 4 per year).

The accident impacts of these two variables were analyzed jointly using two methods: (1) cross-classification analysis, and (2) multiple regression analysis. Either of the methods may be used to estimate the accident impact of signal removal.

The signal removal case study data base used for this analysis comprised a total sample of 164 intersections (exclusive of the 15 intersections with poor sight distance and 12 intersections with insufficient data). A random subset of 43 intersections was selected for use as a validation test set. The remaining subset of 121 intersections was used to carry out the initial cross-classification and multiple regression analyses.

Cross-Classification Method

In this method the sample of intersection accident data was subdivided into different classes of each of the two independent variables. Three class intervals were established for each independent variable, resulting in a three by three, or nine-cell matrix. Each cell of the matrix represents a unique combination of levels of two predictor variables. For each cell, the changes in annual total accident frequency and annual injury accident frequency following signal removal were computed. The cell means provide one estimate of the expected accident outcome for a candidate intersection falling in that cell. Student t tests were performed to determine if each cell mean was statistically different from zero-- i.e., a significant change in accident frequencies was evident for that cell. Cross classification computations were made for average annual changes in both the total accident frequency and the injury accident frequency per intersection. The results are presented in Tables 15 and 16. The results from both matrices were encouraging. The individual cell means for change in total accidents ranged from -2.91 to +2.43 accidents per year, four of the cell means were significantly different from zero, and the trends across the rows and down the columns were generally consistent.

Table 15. Effect of Volume Magnitude and Before Accident Frequency on Accident Impact of Signal Removal

BEFORE ACCIDENT FREQUENCY \ VOLUME MAGNITUDE		NUMBER OF HOURS PER DAY IN WHICH TRAFFIC VOLUMES EQUAL OR EXCEED 60% OF MUTCD WARRANT No. 1			TOTAL
		0	1–4	5 OR MORE	
AVERAGE ANNUAL ACCIDENT FRFQUENCY BEFORE SIGNAL REMOVAL	LESS THAN 1	+.07	+1.26*	+2.43*	+1.10*
	1–3.99	–.16	+.29	–.5	–.01
	4 OR MORE	–2.91*	–1.58*	–.63	–1.95*
TOTAL		–.70*	–.04	+.39	–.31*

*STATISTICALLY SIGNIFICANT AT α = 0.10 OR BETTER

Numbers in the table are <u>changes</u> in average annual accident frequency per intersection following conversion from signal to two way stop control. Plus means accidents increase. Minus means accident decrease following signal removal.

Table 16. Effect of Volume Magnitude and Before Accident Frequency on Injury Accident Impact of Signal Removal.

BEFORE ACCIDENT FREQUENCY \ VOLUME MAGNITUDE		NUMBER OF HOURS PER DAY IN WHICH TRAFFIC VOLUMES EQUAL OR EXCEED 60% OF MUTCD WARRANT No. 1			TOTAL
		0	1-4	5 OR MORE	
AVERAGE ANNUAL ACCIDENT FREQUENCY BEFORE SIGNAL REMOVAL	LESS THAN 1	+.18*	+.45*	+.93*	+.49*
	1-3.99	-.31	0	+.07	-.14
	4 OR MORE	-1.05*	-.56*	+.04	-.63
TOTAL		-.42*	-.07	+.35	-.15

*STATISTICALLY SIGNIFICANT AT α = 0.10 OR BETTER

Numbers in the table are changes in average annual injury accident frequency per intersection following conversion from signal to two-way stop control. Plus means injury accidents increase, minus means injury accidents decrease following signal removal.

Similar results were found for the changes in injury accident frequency. These findings suggest that the two-variable classification table provides a useful way to discriminate between intersections which are conducive to improved safety following signal removal and intersections where safety degradation is likely to occur if signals are removed.

One disadvantage of the cross classification method is that, because of the relatively small sample size (n=121), the number of class intervals for each variable must be kept small and therefore the ranges of the class intervals are large.

Multiple Regression Method

The alternative to cross classification was the multiple regression method. In this approach, each intersection has a unique set of independent variables (i.e. volume magnitude and before accident frequency) and dependent variables (i.e. changes in average annual frequency for total accidents and injury accidents).

Multiple linear regression equations were derived using the 121 intersection analysis subset.

First, for estimating Y_1, the change in average annual accident frequency following signal removal:

$$Y_1 = 0.952 + 0.130X_1 - 0.556X_2$$

Where,

X_1 = Number of hours that satisfy 60 percent of the MUTCD Warrant No. 1 volumes.

X_2 = Average Annual accident frequency prior to signal removal.

This regression equation had a coefficient of multiple correlation R, of 0.62 and a standard error of 1.79.

And for estimating Y_2, the change in average annual injury accident frequency following signal removal:

$$Y_2 = 0.153 + 0.089X_1 - 0.184X_2$$

This regression had a coefficient of multiple correlation, R, of 0.428 and a standard error of 1.12.

The results of the multiple regression anlayses for changes in total accidents and changes in injury accidents were quite similar in terms of separating intersections with increased accidents from those with decreased accidents. This is shown graphically in Figure 4 in which break even lines are plotted for changes in total accidents and injury accidents based on the multiple regression results.

It is believed, based on the results, that accident impact prediction should focus principally on changes in total accident frequency. The absolute value of changes in injury accidents are much smaller and the relationship to predictor variables is weaker as measured by the multiple correlation coefficient. Moreover, many of the intersections in the analysis test set had no injury accidents at all in the before or after period. Accident prediction, especially when applied to individual intersections, is subject to a wide range of variability. Attempting to predict shifts in injury accidents is far more difficult because the variability is superimposed on much smaller estimated absolute values of changes in injury accident frequency. For all of these reasons it was considered prudent to recommend accident impact prediction only for total accidents.

Validation of Accident Prediction Methods

Both the cross-classification and multiple regression methods of accident prediction were subjected to validation tests. This was done utilizing the 43 intersection validation test subset which had been extracted from the total sample prior to developing the prediction models. Predictions of changes in annual accident frequency were made for each of the 43 individual intersections by both prediction methods. The predictions were compared with the actual changes in accident frequency which occurred at each intersection and the resulting prediction errors, $\bar{e}$, were computed.

The following results for the mean value, e, and standard deviation, S_e of the prediction errors were determined.

	Cross - Classification Method	Multiple Regression Method
Mean prediction error, $\bar{e}$	+ 0.019	+ 0.29
Standard deviation of prediction error, S_e	2.57	1.92

Neither of the mean prediction errors are statistically significant (different from zero) at α= 0.10 or less. Therefore we can say that both of the prediction methods are unbiased, i.e. the average prediction error is not different from zero.

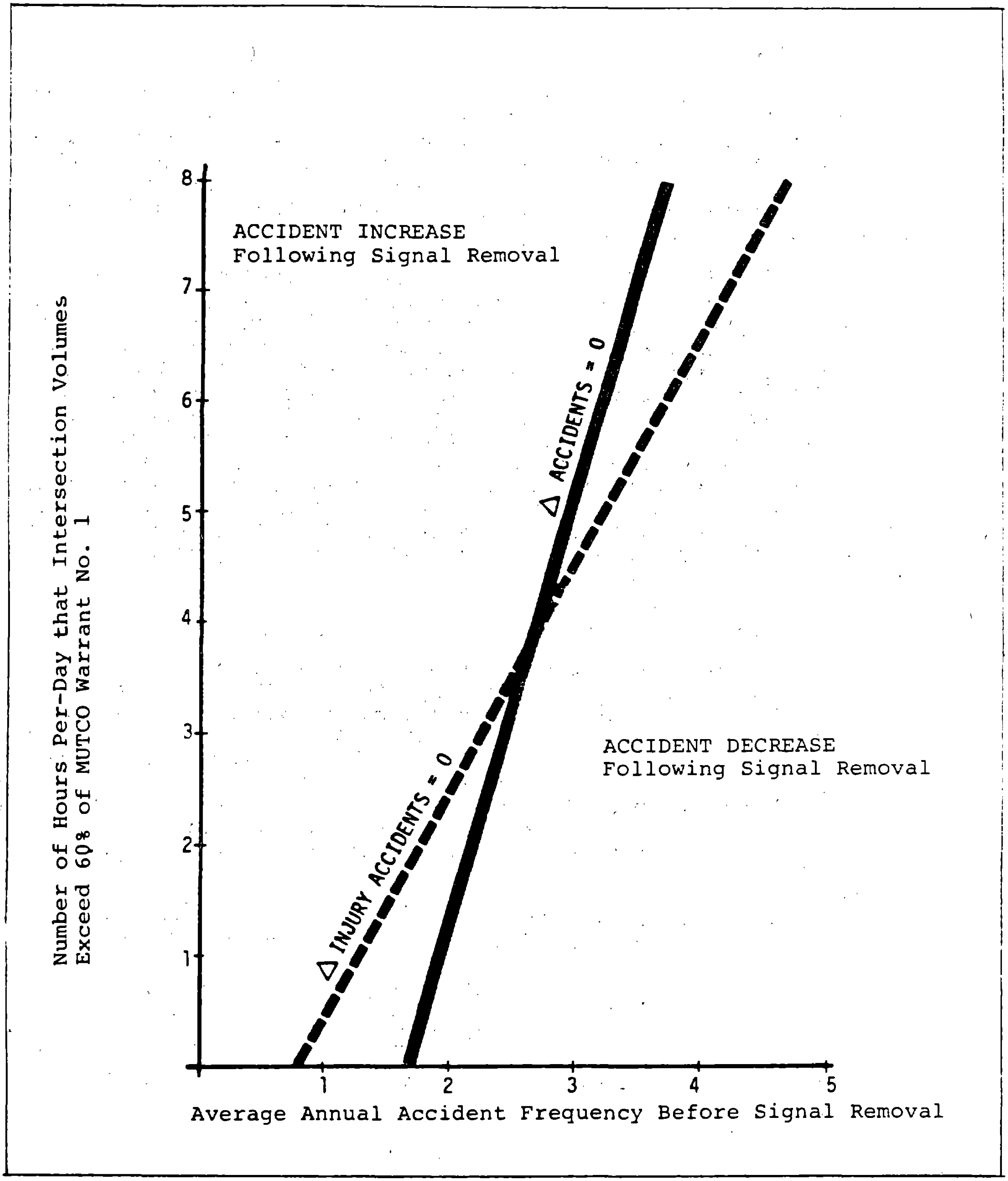


Figure 4. Break Even Lines for Changes in Total Accidents and Changes in Injury Accidents

The results do indicate that the multiple regression method yields slightly less (statistically significant at $\alpha = .05$) error variability. For this reason, it was concluded that the multiple regression method is a slightly better prediction approach in this case.

Another way of assessing the validity of the two prediction methods is shown in Tables 17 and 18, respectively, for the cross-classification and multiple regression methods. These tables subdivide the test intersections into two sets: (1) accident increases predicted, and (2) accident decreases predicted. The <u>actual</u> changes in accident frequencies for each prediction subset are then classified and tabulated.

The results show that both prediction methods were quite effectivein predicting accident impacts of signal removal and conversion to two-way stop. This was especially true when a decrease in accidents was predicted. For example, in the case of cross-classification predictions (Table 17), out of the 20 intersections for which accident <u>decreases</u> were predicted, only 5 intersections experienced increased accident frequency following signal removal. Thirteen of the 20 had decreased accidents as predicted, and the other two experienced no change.

The prediction results were even stronger for the multiple regression method (Table 18). In this case, out of 16 intersection for which accident reductions were predicted, only one actually experienced an increase in accidents following signal removal. Thirteen of the 16 had decreased accidents, as predicted, and the other two intersections had unchanged accident frequences.

The validity of the predictions were also quite strong for the cases where <u>increases</u> in accidents were predicted. However, the most critical test, we believe, is the error rate associated with predicted <u>reductions</u> in accidents. The results highlighted above indicate <u>a low rate</u> of occurrence of such critical errors.

<u>Final Accident Prediction Model</u>

Following the successful validation tests, all of the urban intersection test data (n = 164) were combined and used to derive a final multiple regression equation for estimating changes in average annual accident frequency per intersection resulting from conversion from signal to two-way stop control.

$$Y_1 = 1.01 + 0.139X_1 - 0.605X_2$$

Where X_1 and X_2 are volume magnitude and before accident frequency, as previously defined.

Table 17. Test of Cross Classification Accident Predictions

PREDICTED CHANGE IN ANNUAL ACCIDENT FREQUENCY	NUMBER OF INTERSECTIONS FOR WHICH ACTUAL ACCIDENT FREQUENCY		
	INCREASED	DID NOT CHANGE	DECREASED
INCREASE (23 INTERSECTIONS)	10	7	6
DECREASE (20 INTERSECTIONS)	5	2	13

Table 18. Test of Multiple Regression Accident Predictions

PREDICTED CHANGE IN ANNUAL ACCIDENT FREQUENCY	NUMBER OF INTERSECTIONS FOR WHICH ACTUAL ACCIDENT FREQUENCY		
	INCREASED	DID NOT CHANGE	DECREASED
INCREASE (27 INTERSECTIONS)	14	7	6
DECREASE (16 INTERSECTIONS)	1	2	13

This regression has a coefficient of multiple correlation, R, of 0.675 ($R^2 = 0.455$) and a standard error of 1.79. Curves for various predicted changes in annual accident frequency are shown in Figure 5.

It should be noted that the above equation applies only to urban intersection converted from signal to two-way stop control, and excludes intersections with inadequate corner sight distance.

DISCUSSION

There are several pitfalls in any before/after accident analysis and some of these may be present to some degree in the foregoing assessment of accident impacts of traffic signal removal. For example, many factors that are unrelated can cause a change in accident frequency.

One concern is the nature of the overall trend in accident frequencies and rates. If significant trends exist, they may affect the before and after comparisons. Our signal removal data came from a large number of cities and it was not feasible to investigate background trends in accident frequencies and rates for each city. However, national trends for 1967 through 1976 in urban areas show that for combined non-fatal injury accidents and fatal accidents, the total frequencies were in a gradual uptrend of about 2 percent annually, whereas rates were in a gradual downtrend of just over 2 percent per year. Our study focused on annual accident frequencies before and after signal removal; accident rates could not be calculated at many case study intersections because of the absence of reliable before and after volume data. Thus, one might expect slight increases in accident frequencies from the before and after periods as a historical trend. However, since typical before and after periods were of one to two years duration, (say, for example, 1.5 years from the midpoint of the before period to the midpoint of the after period), the historical trend background would be an increase in accident frequency of only about 3 percent. It is believed, therefore, that any confounding of treatment impacts and historical trends in this study were negligible.

Another concern in before and after accident comparisons is the statistical phenomenon of "regression to the mean". This simply means that if the accident frequency or rate at a given intersection in the before period is very high compared with the average of the set being analyzed, the after period frequency or rate is likely to get lower (i.e., move toward the mean). The reverse also tends to be true; locations with extremely low accident experience before would tend to get higher.

This phenomenon is undoubtedly present to some degree in our finding that intersections with low before accident frequency have increased accidents following signal removal and

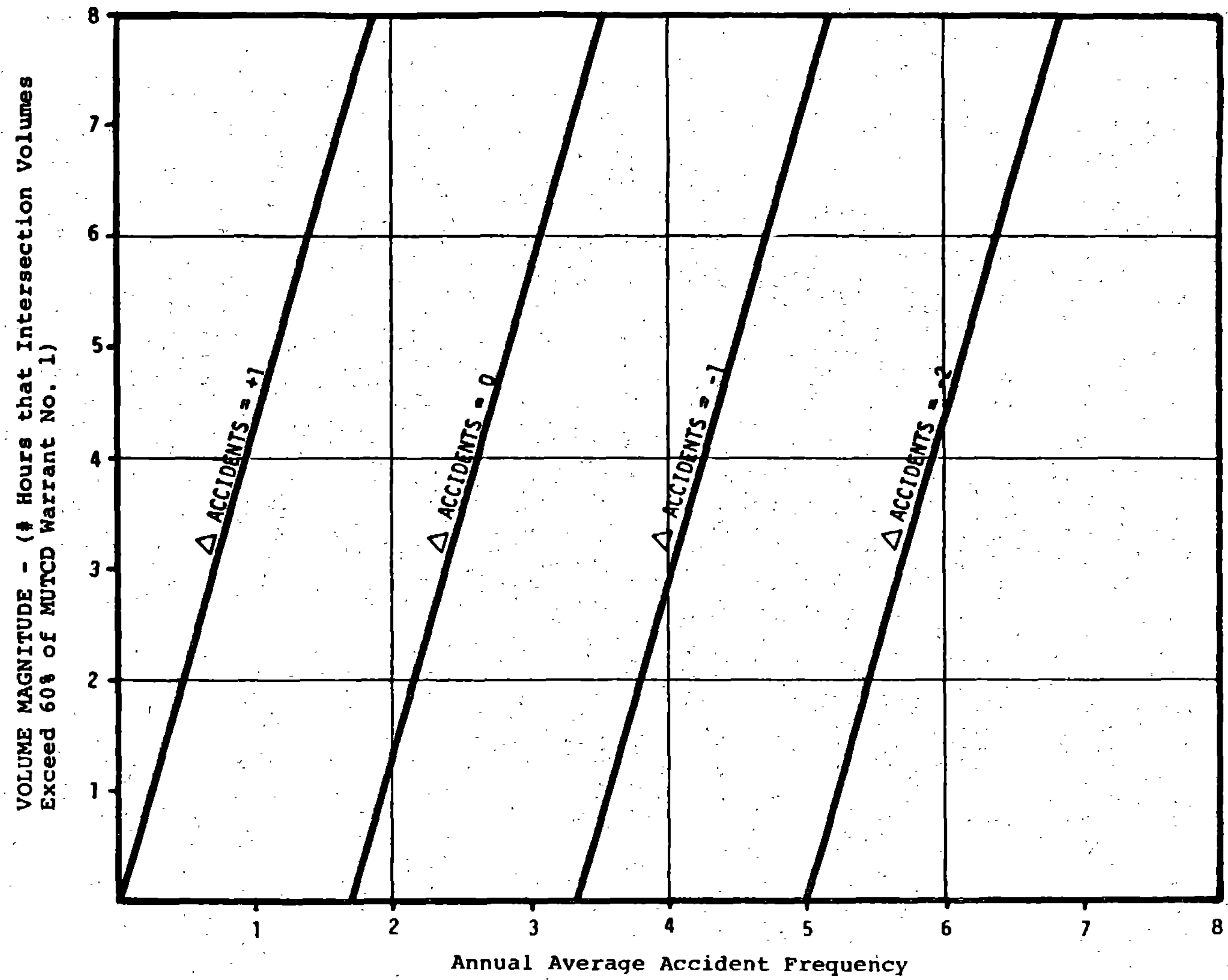


Figure 5. Predicted Changes in Average Annual Accident Frequency Following Signal Removal (Conversion to Two-Way Stop Control)

vice versa. In statistical terms, however, we were not selecting "extreme" cases for treatment which are the type most affected by the regression to the mean phenomenon. Our highest class of before accident frequency of 4 or more accidents per year (see Table 14) for urban signals converted to two-way stop control had a before average of only 5.99 accidents per year. This is a "moderate" accident frequency for the total population of signalized urban intersections; hence the likelihood is small that regression to the mean had any major effect on our findings.

STOPS, DELAYS, AND FUEL CONSUMPTION IMPACTS

This chapter presents the findings of the assessment of the impacts of signal removals on intersection stops, delays, and fuel consumption. The analysis included developing a set of nomographs and supporting calculation procedures so that these traffic performance impacts can be estimated for any set of intersection traffic volume conditions. A limited set of specific case example impacts were also completed to provide the reader with a perspective of how signal performance affects stops, delays and fuel consumption.

METHODOLOGY

Calculations of stops and delays relied primarily on the calculation procedures contained in the Swedish Capacity Manual, 1976 (21). In the case of four-way stops, the intersection delay (exclusive of acceleration and deceleration delay) was estimated from findings reported by Benioff, et al. in "A Study of Clearance Intervals, Flashing Operation and Left Turn Phasing," Volume 3, Flashing Operation, 1978 (22).

Estimates of "Excess Fuel Consumption", i.e., that portion attributable to intersection stop cycles and idling delay time, were calculated using the following coefficients:

1 stop from 30 mph = 0.0045 gallons
1 second of idling = 0.00015 gallons

These coefficients were estimated for passenger cars on the basis of fuel consumption data from a variety of sources.

CASE EXAMPLE FINDINGS

Data from two representative case examples were used.

1. From the signal removal research study data base, all intersections of 4-lane main road and 2-lane side road, for which detailed volume data were available, were used as one case. Traffic volumes of these 19 intersections were averaged for the 4 highest hours of the day for the analysis. Results are shown in Table 19.

Table 19. Performance Summary for Intersection Of Four-Lane Major and Two-Lane Minor (Average Case From Research Data Base)

Traffic Volumes (vph) Main Road - 832 Side Road - 150 Total - 982			
Total Intersection Performance	Signal Control*	2-Way Stop	4-Way Stop
Stop Probability	0.46	0.17	1.00
Average Delay/Vehicle (seconds)			
Idle	7.1	1.3	2.7
Accel./Decel.	6.8	2.5	12.0
Total	13.9	3.8	14.7
Excess Fuel Consumption Gallons/Veh.	0.00316	0.00097	0.00490
Energy Savings Gallons/Veh.	Base	0.00219	(0.00174)

* Cycle = 60 seconds
Side Street Green = 18 seconds

2. From the trial application of signal removal criteria in Terre Haute, Indiana, data were available from eight intersections of 2-lane main roads and 2-lane side roads. Volume data from these intersections were averaged to form 2 cases:

   - The average of the 2 peak hours of the day.

   - The average of the remaining 22 non-peak hours of the day.

The Terre Haute case study results are summarized in Table 20. These case examples represent typical conditions at intersections where signal removal is being pursued. Also, since both peak and non-peak conditions are analyzed, the range of traffic volume magnitudes is quite wide. The most interesting results of these case analyses is the strong similarity of findings. The general results are summarized as follows:

- <u>When a traffic signal is replaced by 2-way stop control</u>

  - Average delay per vehicle is reduced by approximately <u>10 seconds</u> (5 to 6 seconds of which is idling delay).

  - Stop probability is reduced from about 0.50 to about 0.20 (depending on the ratio of main road to side road volumes and the magnitude of main road left turning vehicles).

  - Excess fuel consumption is reduced by about 0.0022 gallons per vehicle (this finding is very consistent).

- <u>When a traffic signal is replaced with four-way stop control</u>

  - Average overall delay per vehicle is only slightly reduced, <u>but idling delay is reduced</u> by about 5 seconds.

  - Stop probability is approximately <u>doubled</u>, from about 0.50 to 1.00.

Table 20. Performance Summary For Average of Eight Terre Haute Intersections (Two Lane Major and Two Lane Minor)

	2 PEAK HOURS			22 NON PEAK HOURS		
Traffic Volume (vph)						
Main Road	600			264		
Side Road	150			66		
Total	750			330		
Total Intersection Performance	Signal Control	2-Way Stop	4-Way Stop	Signal Control*	2-Way Stop	4-Way Stop
Stop Probability	0.52	0.22	1.00	0.51	0.21	1.00
Average Delay/Vehicle (seconds)						
Idle	7.3	1.8	2.2	6.4	0.7	1.6
Accel/Decel	8.8	3.4	12.0	8.5	3.6	12.0
Total	16.1	5.2	14.2	14.9	4.3	13.6
Excess Fuel Consumption Gallons/veh	0.00345	0.00127	0.00483	0.00323	0.00104	0.00474
Energy Savings Gallons/veh	BASE	0.00218	(0.00138)	BASE	0.00219	(0.00151)

*Cycle = 50 seconds
Side Street Green = 15 seconds

- excess fuel consumption is increased by about 0.0015 gallons per vehicle. The savings due to less idling delay are not nearly enough to overcome the energy waste due to doubling the number of stops.

In all of the above calculations, traffic signals are assumed to be set with near optimum cycles and splits (subject to minimum green time constraints for adequate pedestrian crossing time). Also, these calculations are for isolated intersections.

NOMOGRAPHS FOR DELAYS, STOPS, AND EXCESS FUEL CONSUMPTION

The preceeding case examples gave relatively consistent signal removal impact results for varying conditions. However, to be more precise, impacts should be estimated on the basis of the unique design and traffic volume characteristics of the candidate intersection. To aid in this process, a set of intersection delay, stops, and excess fuel consumption nomographs have been prepared for use in comparing traffic signal control and two-way stop control.

Nomographs were prepared for 6 different types of intersection design, as illustrated in Figure 6:

- 2-lane major, 2-lane minor
  - 4-way intersection
  - T-intersection
- 4-lane major, 2-lane minor
  - 4-way intersection
  - T-intersection
- 4-lane major, 4-lane minor
  - 4-way intersection
  - T-intersection

For each type of intersection, calculations of intersection idling delay (i.e. delay waiting in queue at the signal or stop sign), intersection total delay (i.e. idling delay plus deceleration and acceleration delay), intersection stops, and excess fuel consumption due to stops and idling were calculated for both signal control and 2-way (minor road) stop sign control.

All nomograph calculations are based on the assumption that the intersection is not in close proximity to neighboring signals and, therefore, vehicle arrivals follow a random distribution. (The range of differences in stops and delays with adjacent, coordinated signals on the main road is discussed in a subsequent section.)

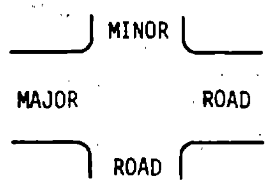
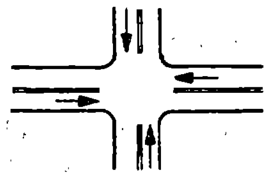
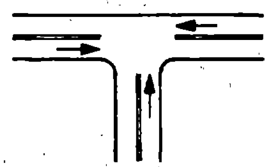
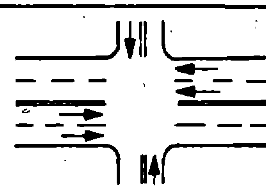
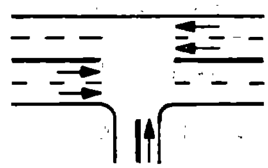
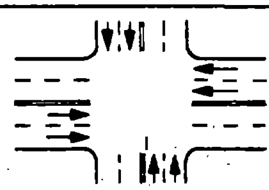
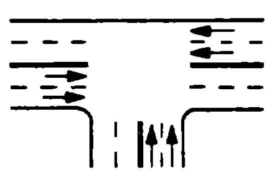
INTERSECTION TYPE	ILLUSTRATION 	NOMOGRAPH FIGURE NUMBERS	
		IDLING & TOTAL DELAY	STOPS & FUEL
4-WAY INTERSECTION, 2-LANE MAJOR ROAD, 2-LANE MINOR ROAD.		7	8
T-INTERSECTION, 2-LANE MAJOR ROAD, 2-LANE MINOR ROAD.		9	10
4-WAY INTERSECTION, 4-LANE MAJOR ROAD, 2-LANE MINOR ROAD.		11	12
T-INTERSECTION, 4-LANE MAJOR ROAD, 2-LANE MINOR ROAD.		13	14
4-WAY INTERSECTION, 4-LANE MAJOR ROAD, 4-LANE MINOR ROAD.		15	16
T-INTERSECTION, 4-LANE MAJOR ROAD, 4-LANE MINOR ROAD.		17	18

Figure 6. List Of Nomographs By Intersection Type

For the traffic signal cases, near optimum signal timing was assumed with a 50 second signal cycle and equal degree of saturation phase splits (subject to a mimimum green time constraint of 15 seconds). In practice, traffic signal timing is almost always sub-optimum and typically ranges from 10 to 20 percent less effective than optimum timing. Hence, for the isolated signal case, the savings in delay, stops and fuel resulting from signal removal are somewhat conservative. In general, however, as seen in a subsequent section, if adjacent interconnected and well coordinated signals are present on the main road, the traffic performance under signal control can be significantly better (and the benefits of signal removal less) than for the isolated signal case.

Each nomograph is constructed to permit estimation for any combination of main road and side road hourly traffic volumes.

Plotted on the horizontal axis of each graph is "side road volume per approach", in vehicles per hour. For 4-way intersections, this value is the average of the two side road approach volumes. For T-intersections, this value equals the approach volume on the only side road approach.

Plotted as a family of lines in the body of each nomograph is "total main road volume", in vehicles per hour. This value is equal to the sum of the two approach volumes on the main road.

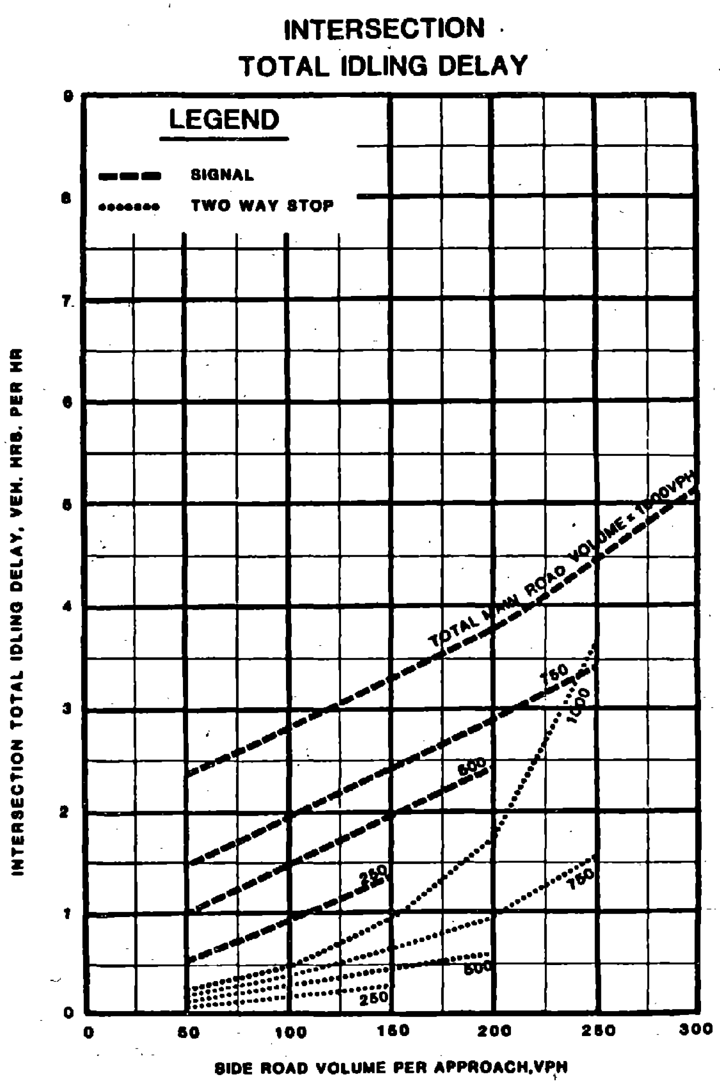
Plotted on the vertical axis of each graph is the variable being estimated. There are four graphs for each intersection type, one for each of the following variables of interest:

- Intersection total idling delay, veh. hrs. per hr.
- Intersection total delay, veh. hrs. per hr.
- Intersection total stops, veh. stops per hr.
- Total intersection excess fuel consumption, gal. per hr.

If desired, the above estimates can be converted into "per vehicle averages" simply by dividing by total intersection approach volume and, in the case of delay, converting units from hours to seconds.

The nomographs are presented in Figures 7 through 18, organized according to the list in Figure 6.

One word of caution is appropriate with respect to estimating characteristics at 4-way intersections. If the 2 side road volumes are substantially different (e.g., they differ by



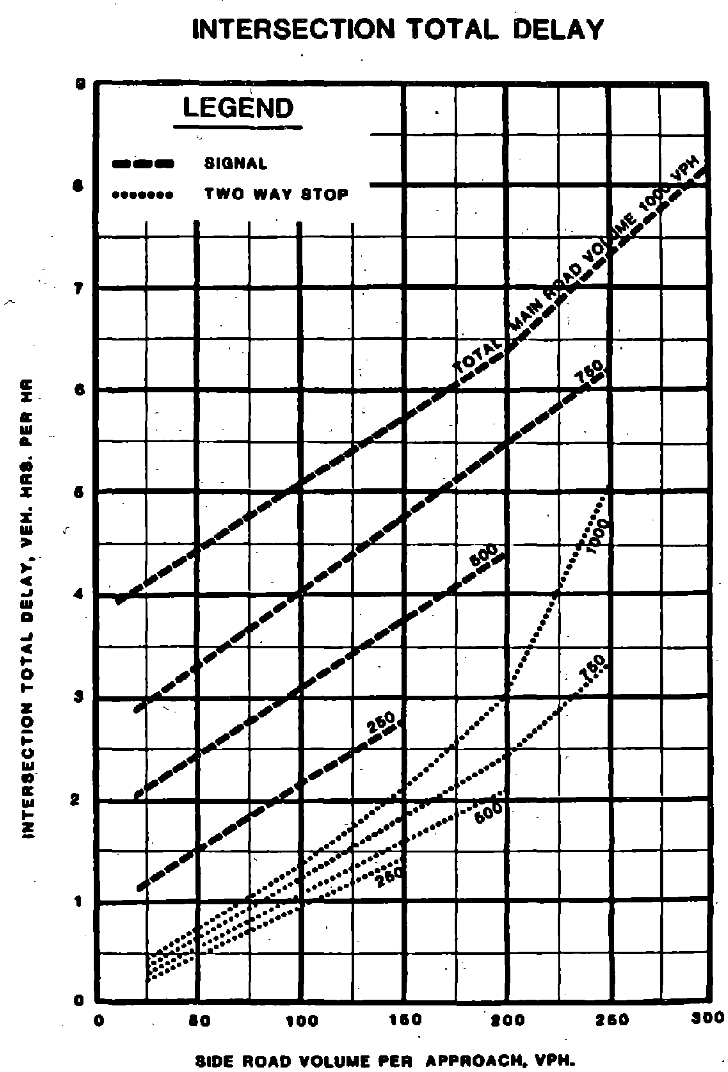


FIGURE 7 IDLING AND TOTAL DELAY

(FOUR WAY INTERSECTION: TWO LANE MAJOR, TWO LANE MINOR)

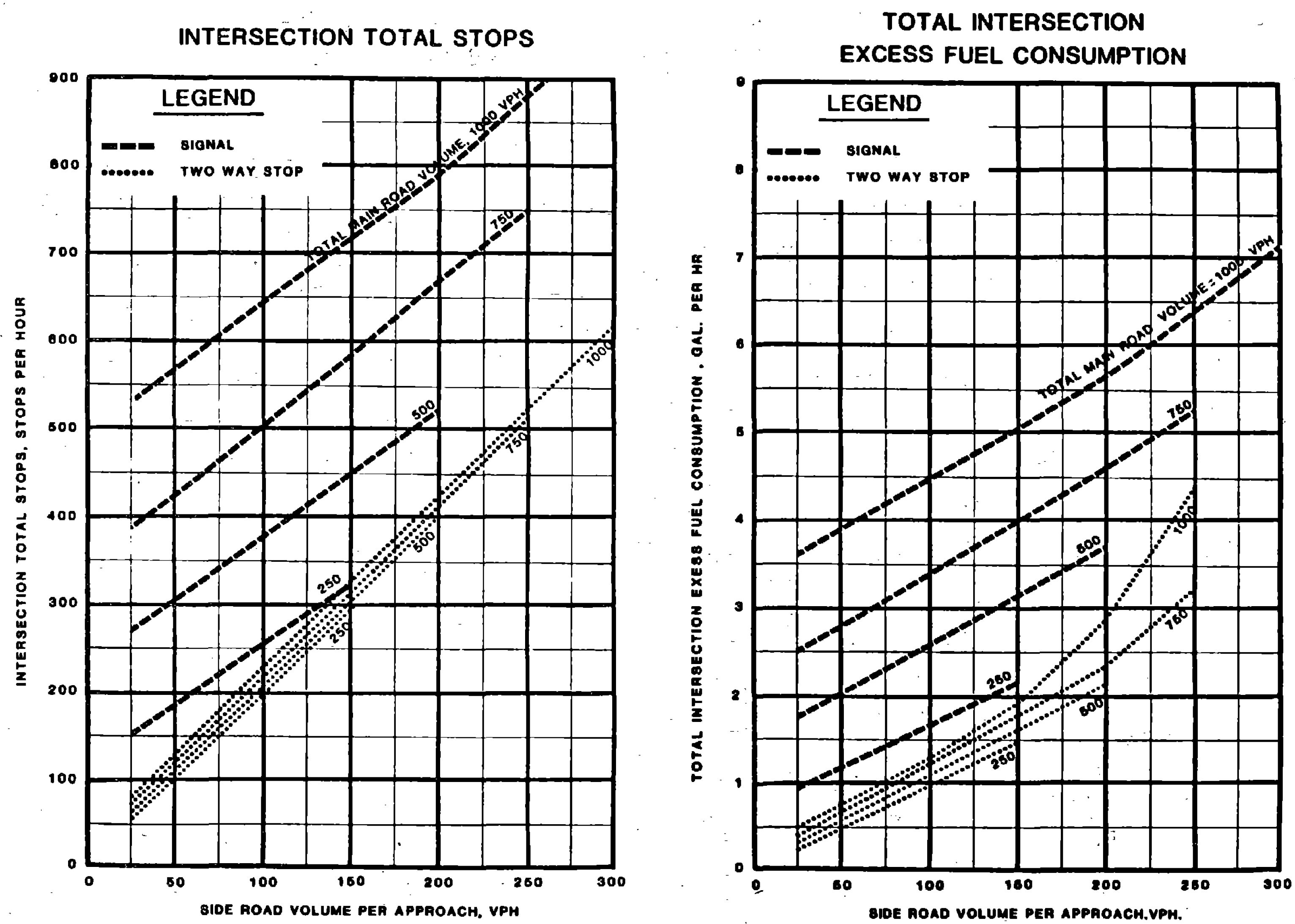


FIGURE 8 STOPS AND EXCESS FUEL CONSUMPTION
(FOUR WAY INTERSECTION: TWO LANE MAJOR, TWO LANE MINOR)

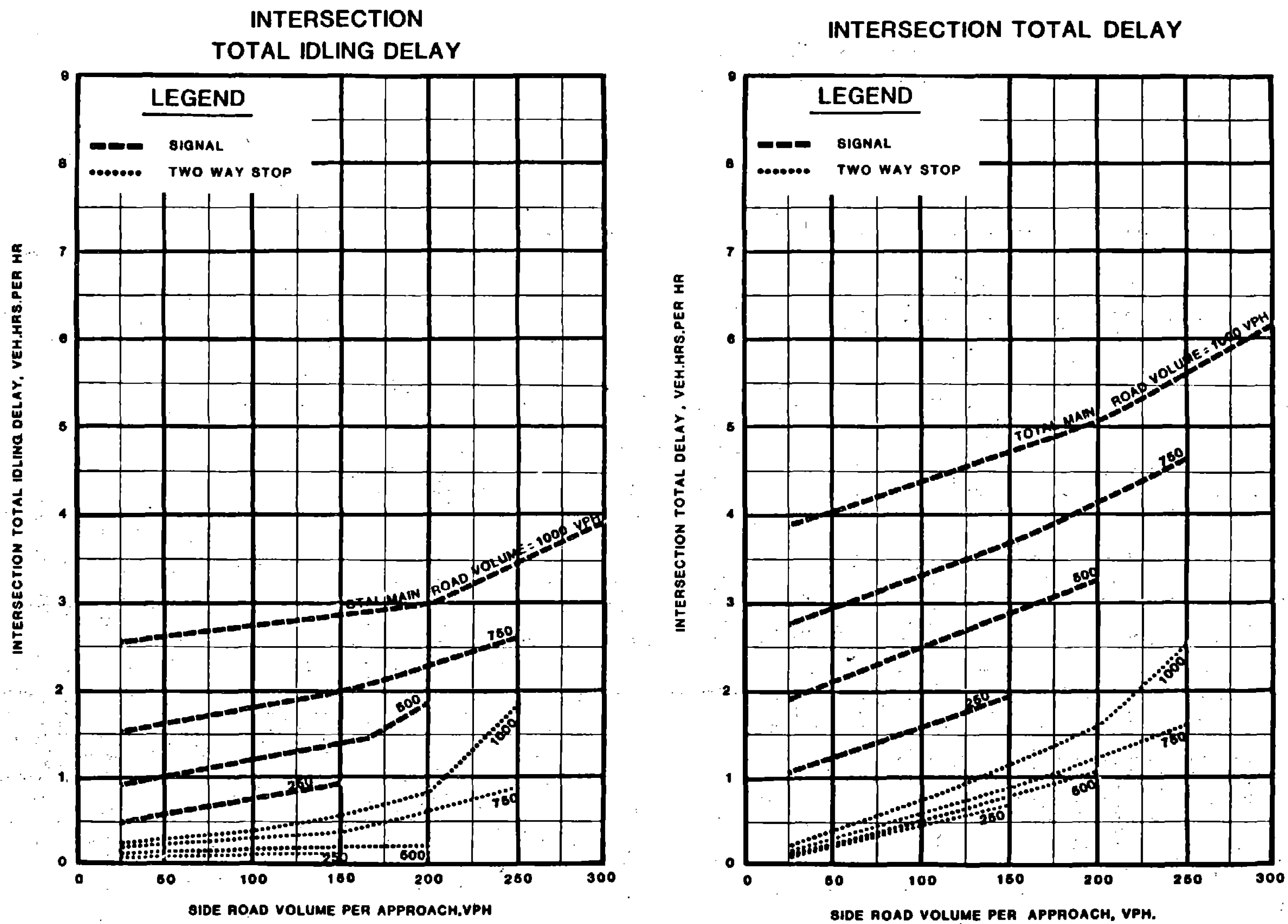


FIGURE 9 IDLING AND TOTAL DELAY
("T" INTERSECTION: TWO LANE MAJOR, TWO LANE MINOR)

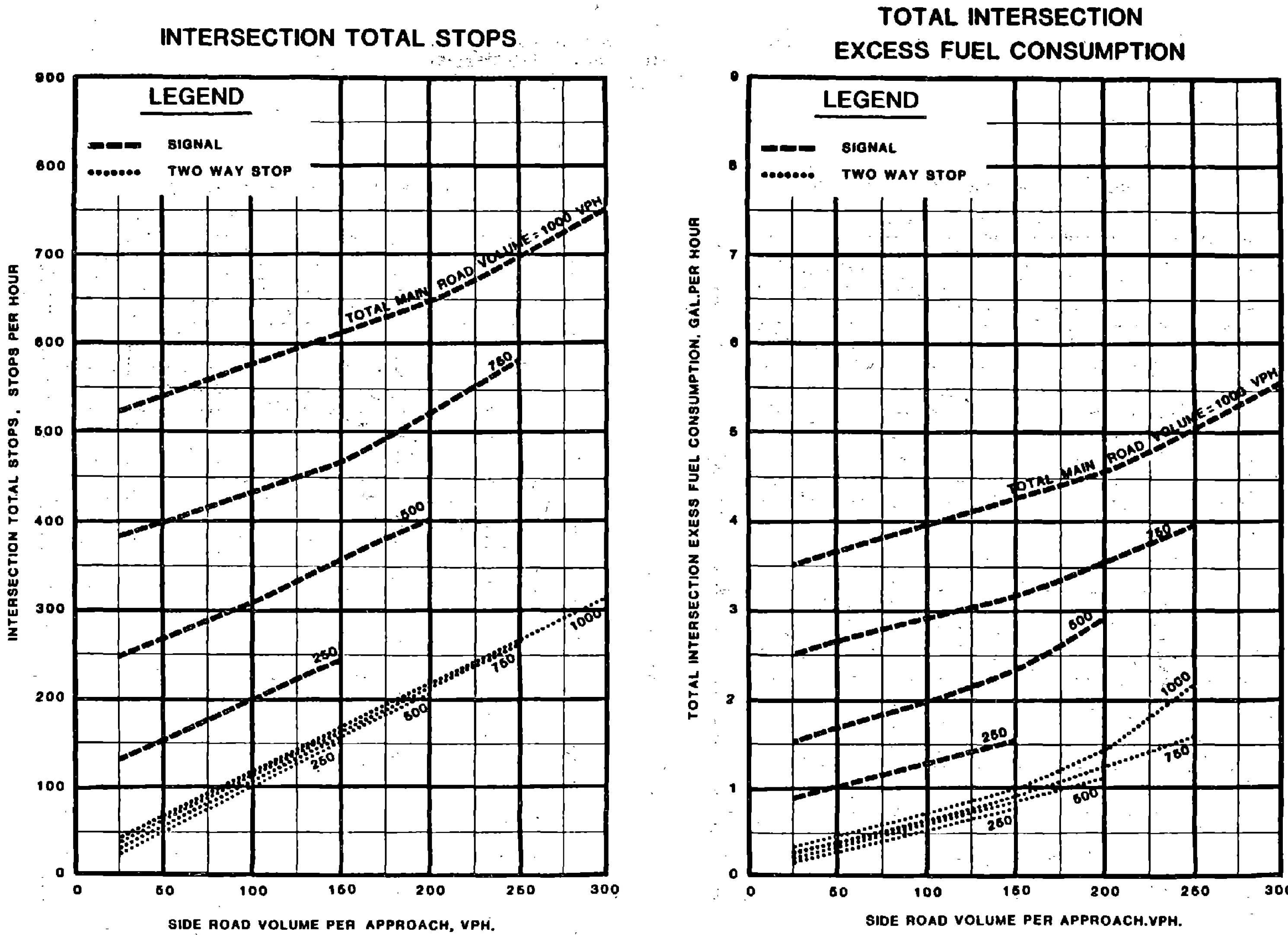
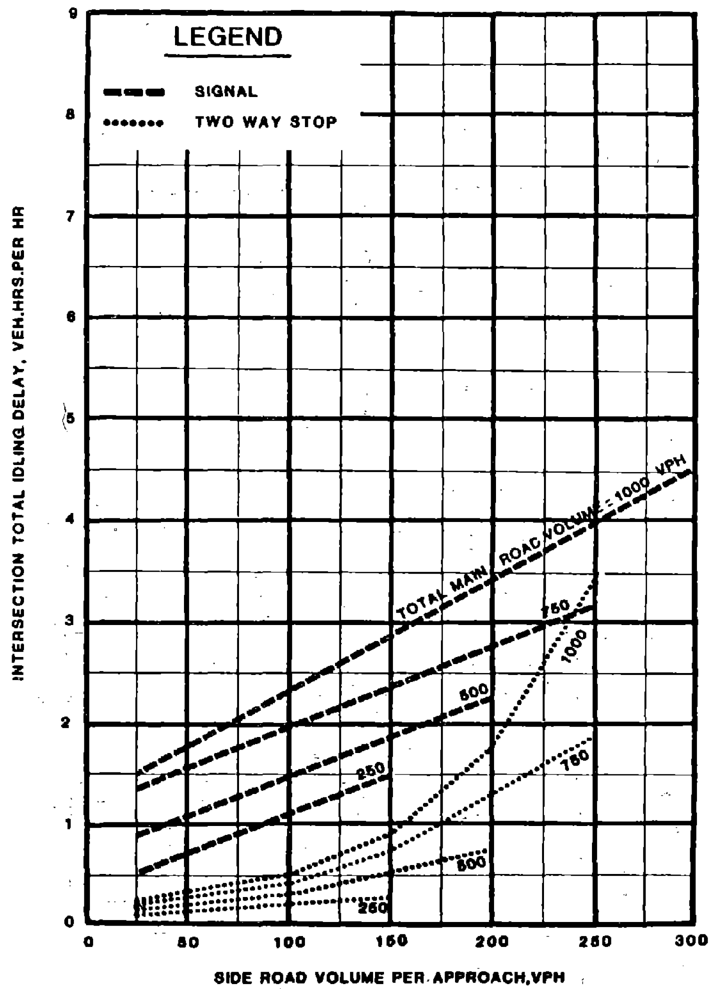


FIGURE 10 STOPS AND EXCESS FUEL CONSUMPTION
("T" INTERSECTION: TWO LANE MAJOR, TWO LANE MINOR)

INTERSECTION TOTAL IDLING DELAY



INTERSECTION TOTAL DELAY

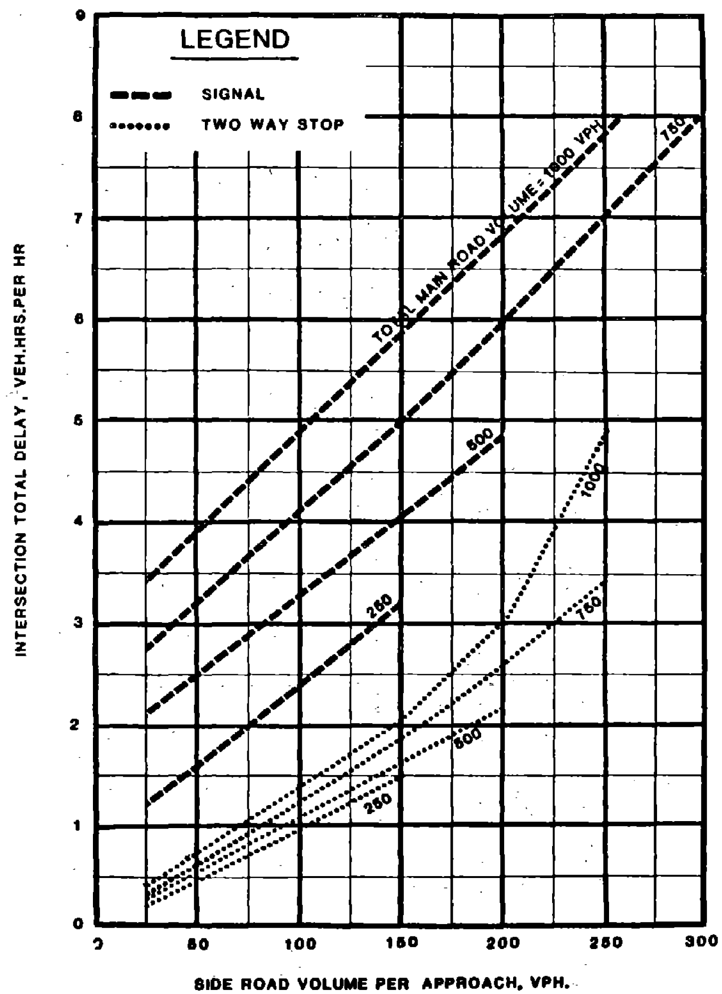
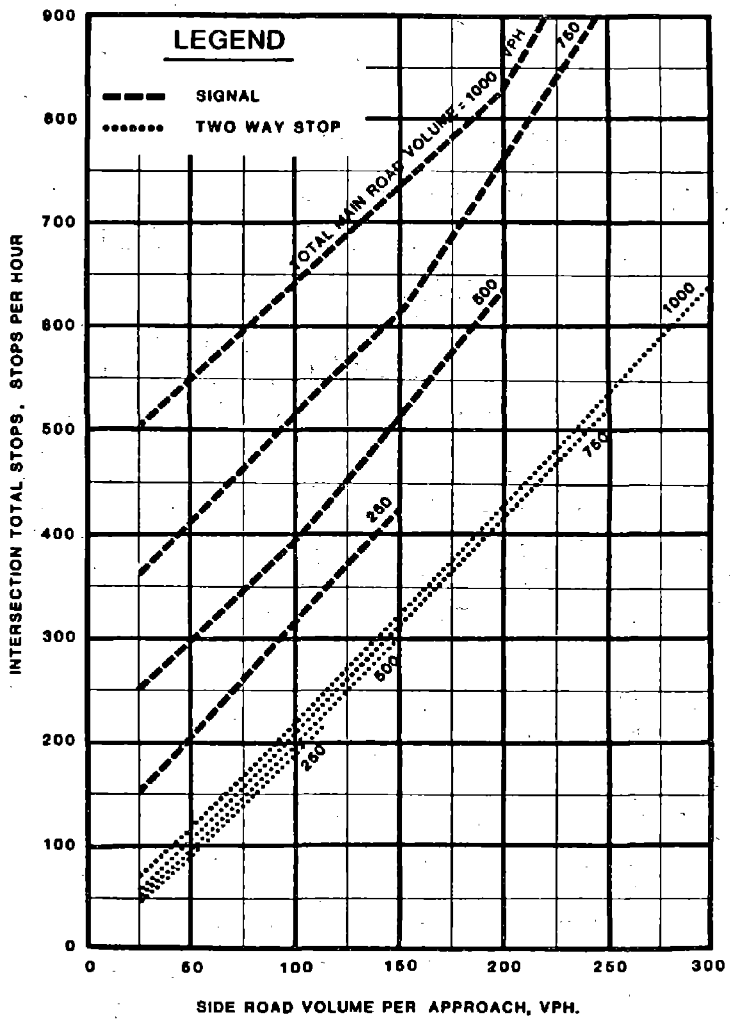


FIGURE 11 IDLING AND TOTAL DELAY
(FOUR WAY INTERSECTION: FOUR LANE MAJOR, TWO LANE MINOR)

INTERSECTION TOTAL STOPS



TOTAL INTERSECTION EXCESS FUEL CONSUMPTION

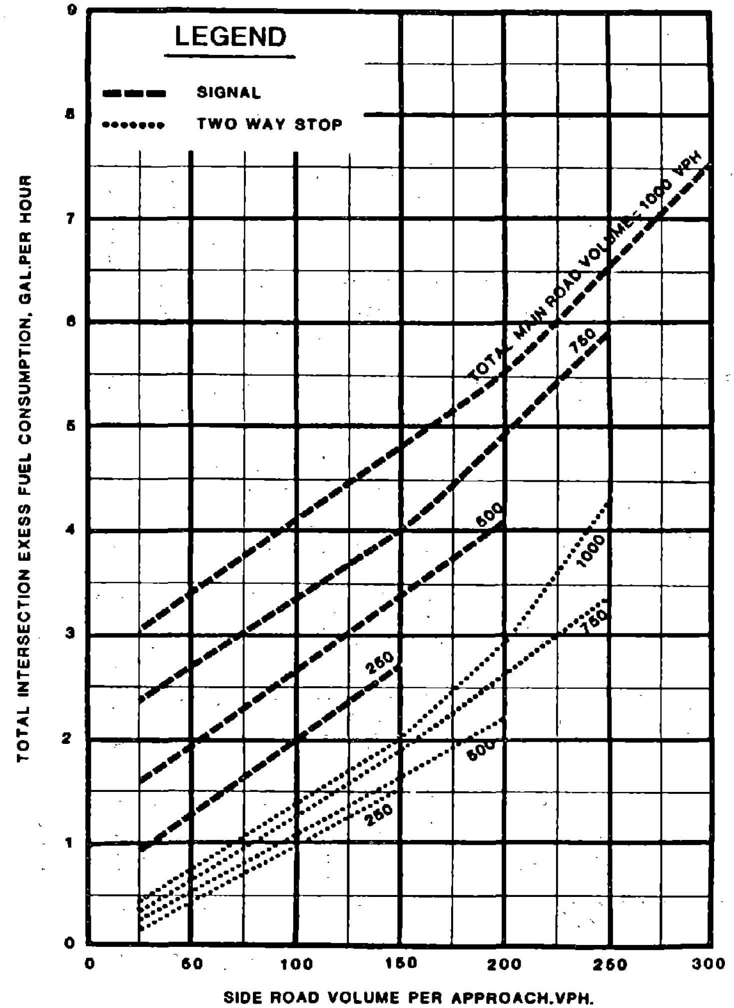
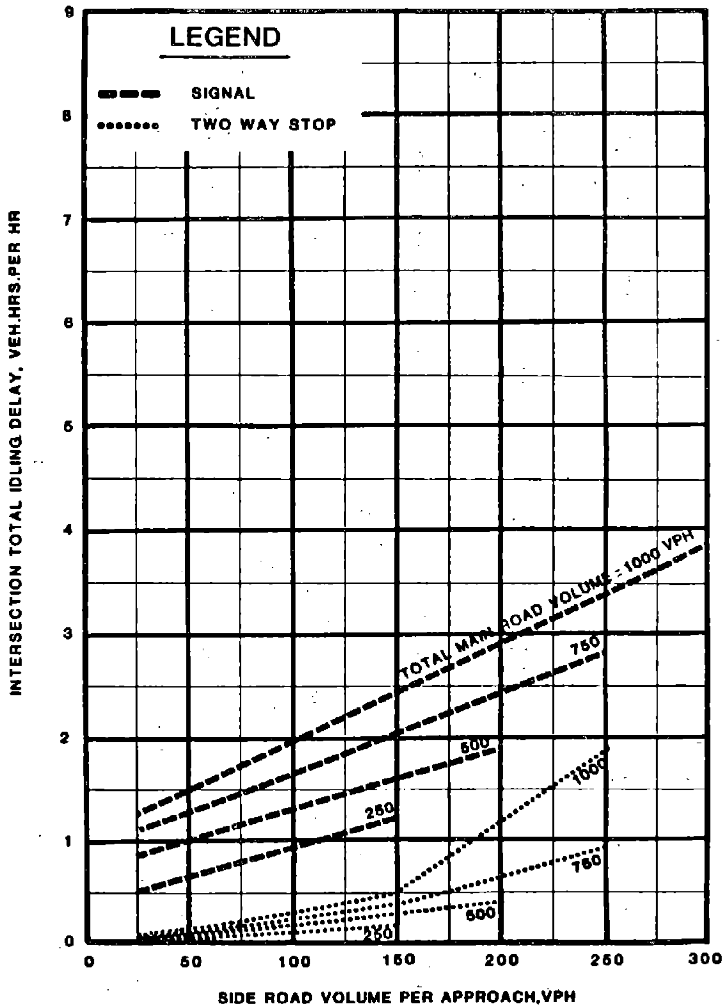


FIGURE 12 STOPS AND EXCESS FUEL CONSUMPTION
(FOUR WAY INTERSECTION: FOUR LANE MAJOR, TWO LANE MINOR)

INTERSECTION TOTAL IDLING DELAY



INTERSECTION TOTAL DELAY

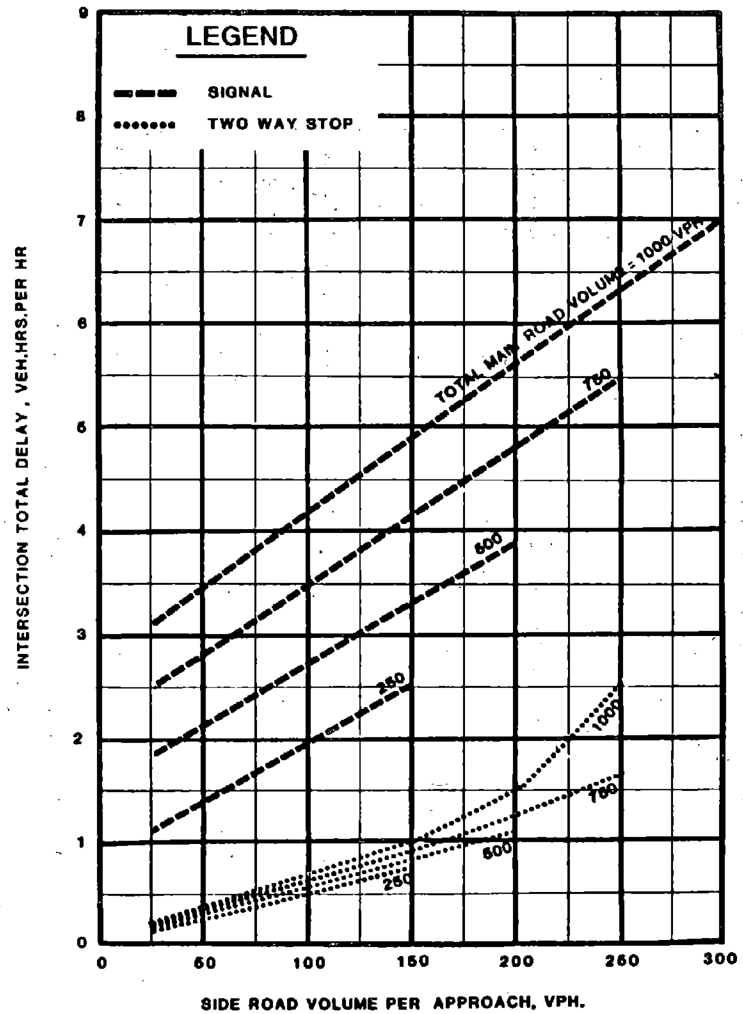
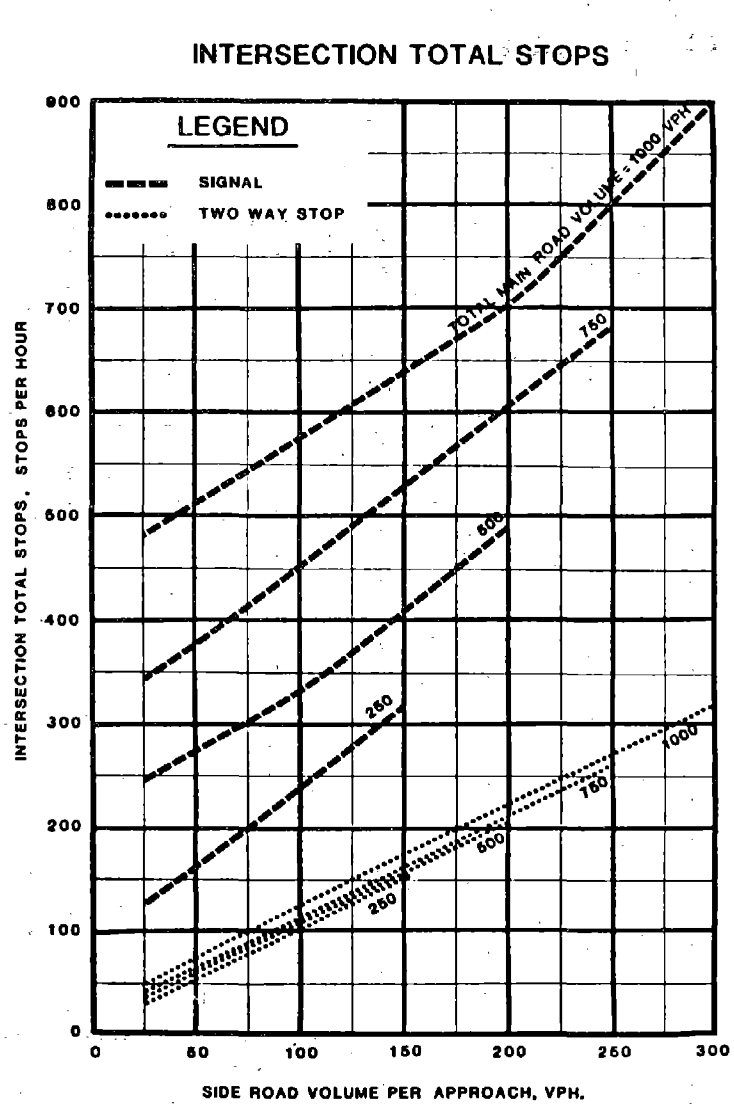


FIGURE 13 IDLING AND TOTAL DELAY
("T" INTERSECTION: FOUR LANE MAJOR, TWO LANE MINOR)



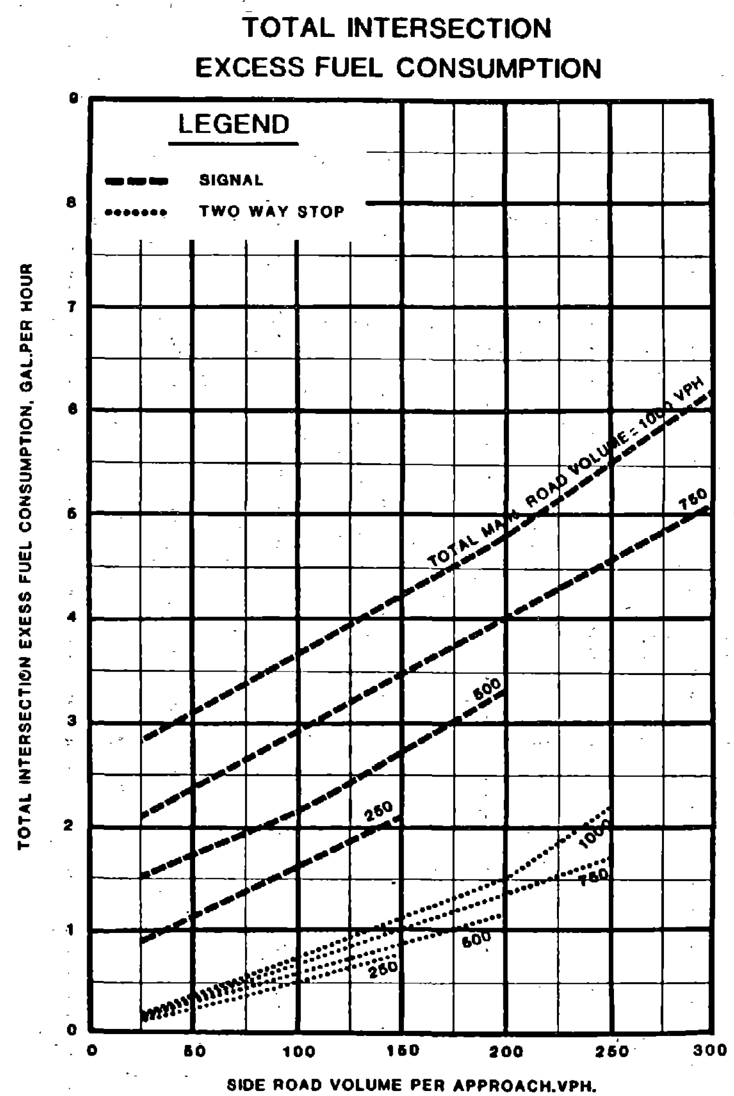


FIGURE 14 STOPS AND EXCESS FUEL CONSUMPTION
("T" INTERSECTION: FOUR LANE MAJOR, TWO LANE MINOR)

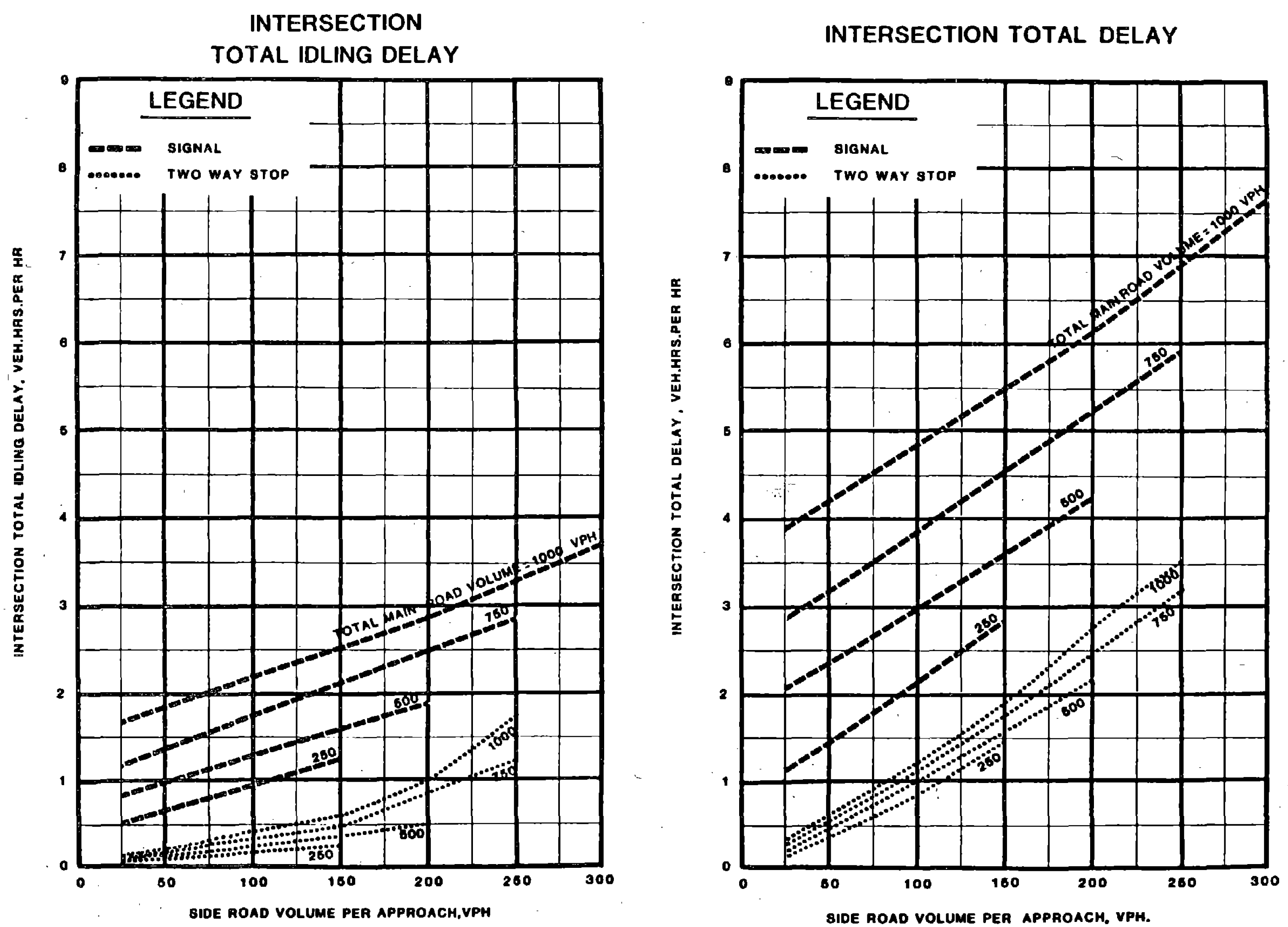
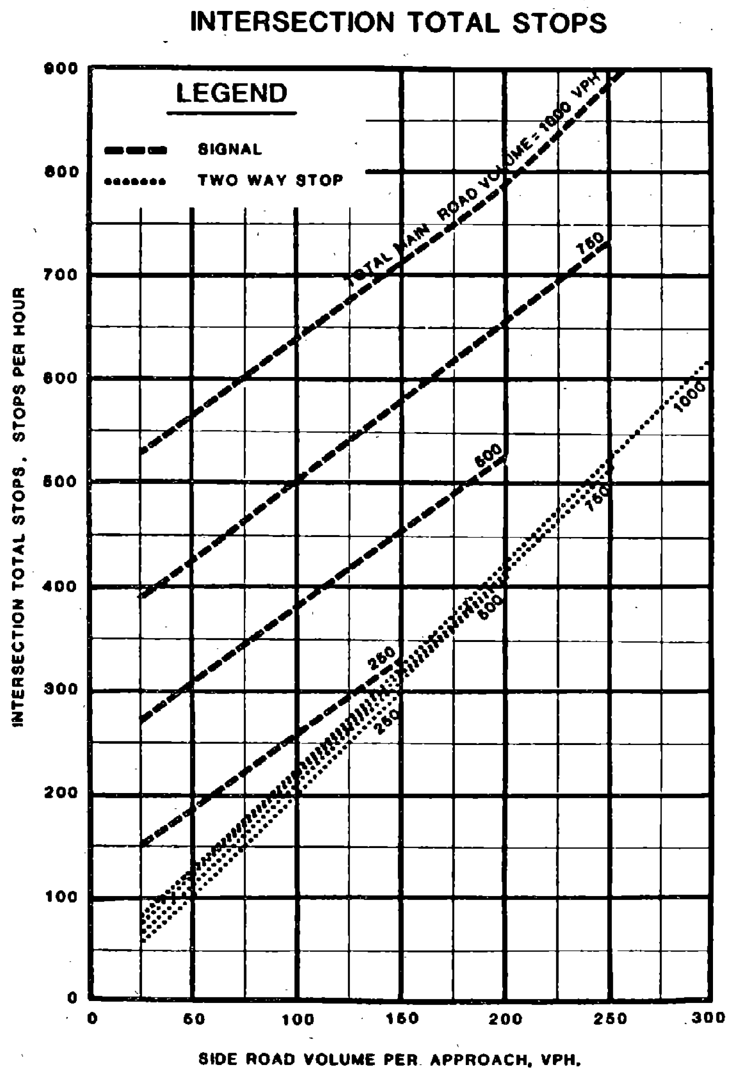


FIGURE 15 IDLING AND TOTAL DELAY
(FOUR WAY INTERSECTION: FOUR LANE MAJOR, FOUR LANE MINOR)



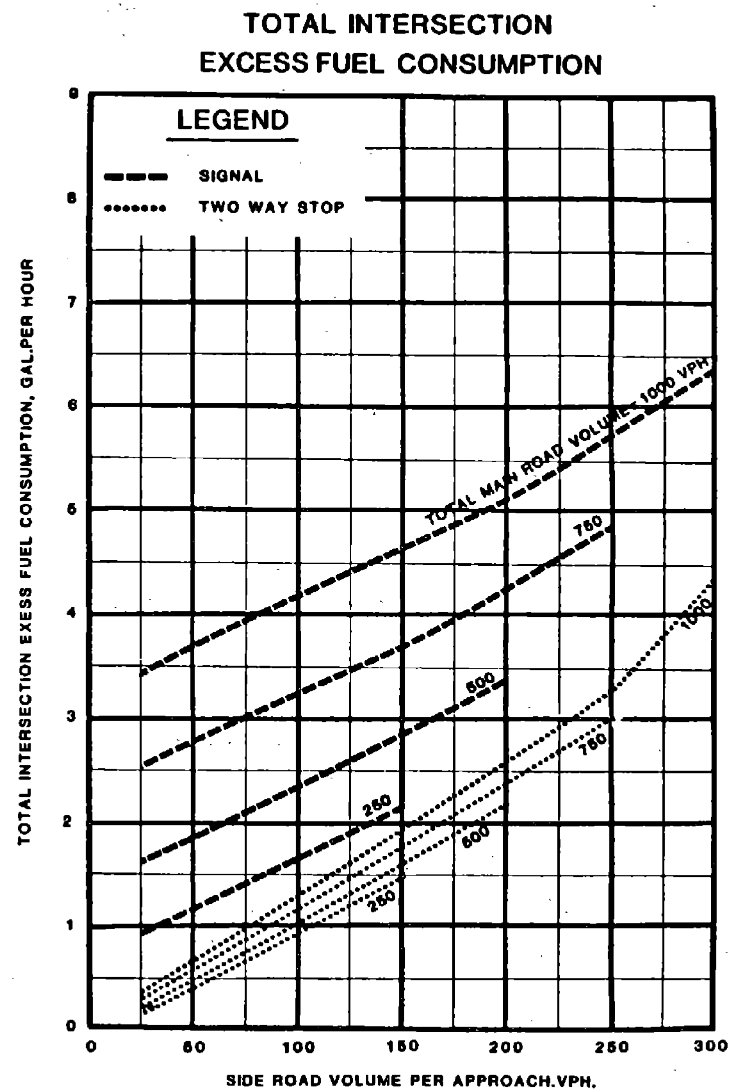
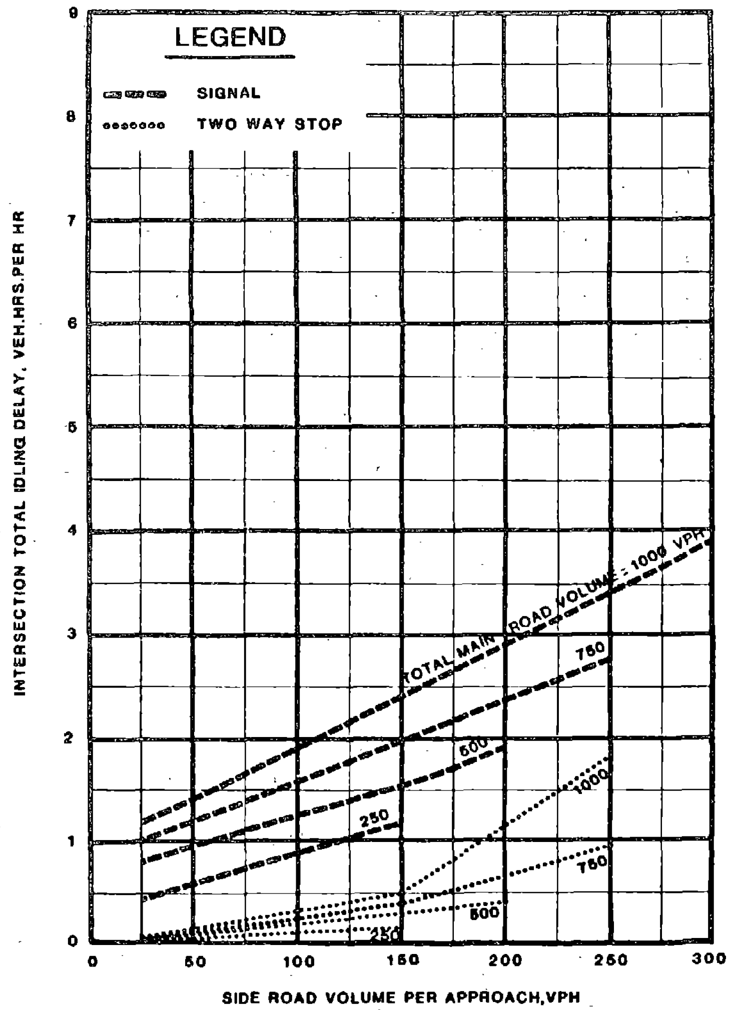


FIGURE 16 STOPS AND EXCESS FUEL CONSUMPTION
(FOUR WAY INTERSECTION: FOUR LANE MAJOR, FOUR LANE MINOR)

INTERSECTION
TOTAL IDLING DELAY



INTERSECTION TOTAL DELAY

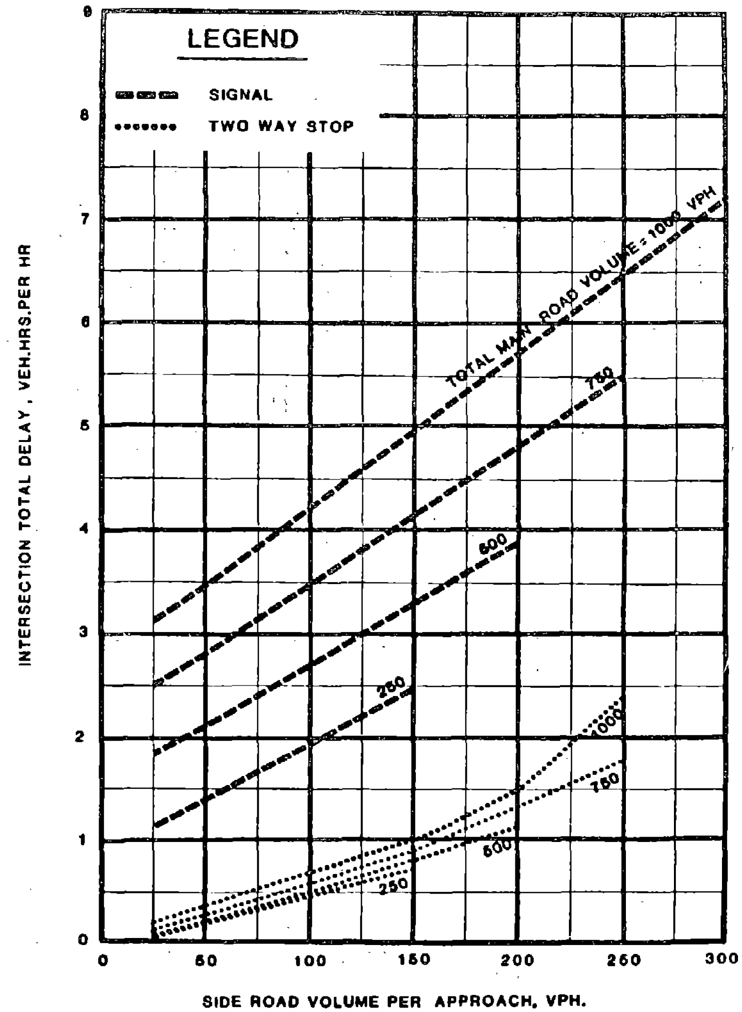
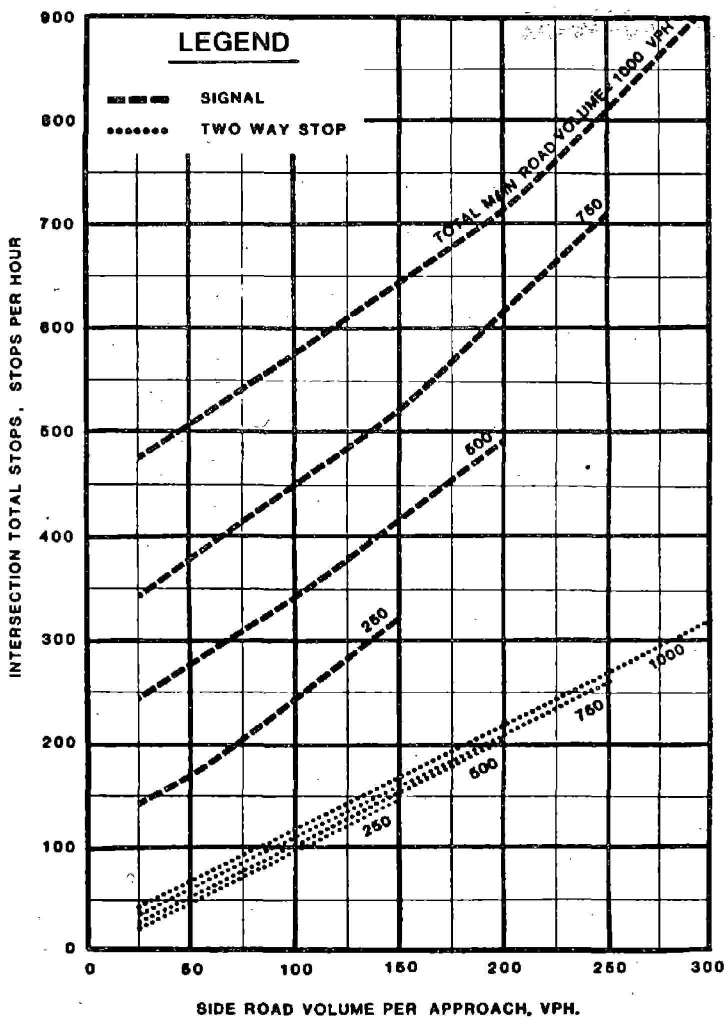


FIGURE 17 IDLING AND TOTAL DELAY
("T" INTERSECTION: FOUR LANE MAJOR, FOUR LANE MINOR)

INTERSECTION TOTAL STOPS



TOTAL INTERSECTION EXCESS FUEL CONSUMPTION

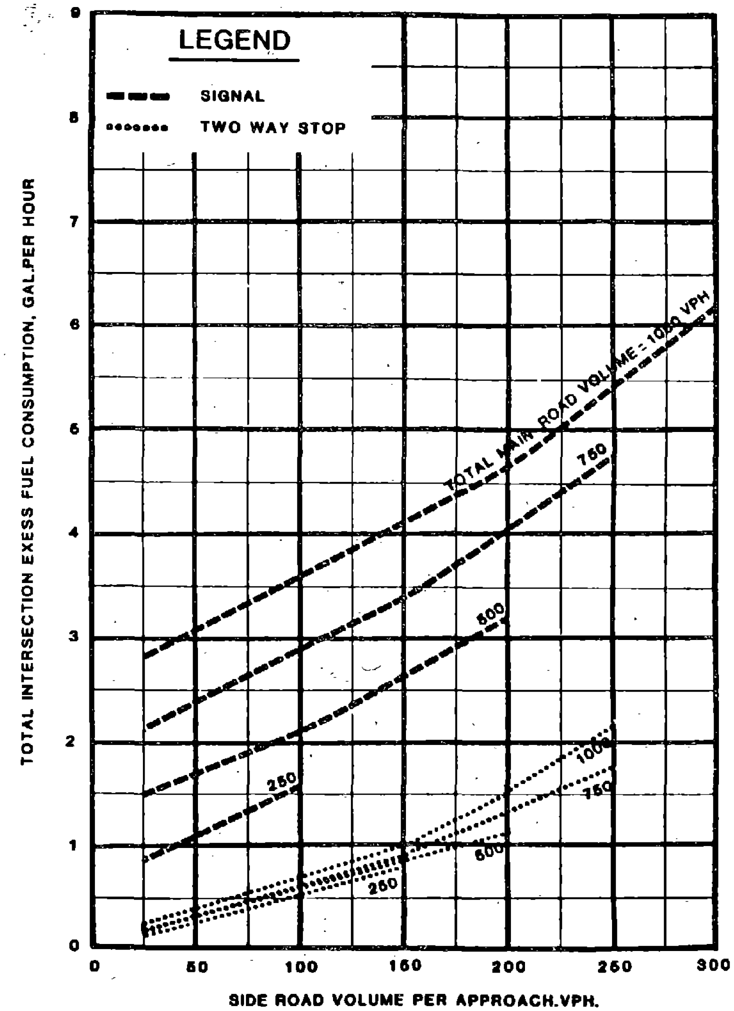


FIGURE 18 STOPS AND EXCESS FUEL CONSUMPTION
("T" INTERSECTION: FOUR LANE MAJOR, FOUR LANE MINOR)

by more than 25% or so), make separate estimates by plotting each side road volume and then average the two estimates.

The user should not attempt to estimate to any closer precision than 2 significant digits for any of the variables. Graphical interpolation accuracy simply does not justify attempting greater precision, nor is it warranted for a "generalized" set of nomographs.

EXAMPLES OF NOMOGRAPH ESTIMATES

This section presents the results of example calculations of estimates of intersection delays, stops, and excess fuel consumption using the nomographs. Six examples are calculated, one for each of the intersection design types represented in the set of nomographs. Various volume levels are selected to indicate example results covering a substantial range of volume conditions. Identical total main road volumes are chosen for the comparable pairs of 4-way intersections and T-intersections in order to permit an examination of the effect of this difference in intersection type.

The results of the six examples are presented in Table 21 and 22. Sufficient detail is presented to permit the reader to use the nomographs to check each example as a training exercise.

The reader is reminded that the nomographs are entered with hourly traffic volumes and the resulting estimates are hourly totals of vehicle hours of idling delay, vehicle hours of total delay, stops, and gallons of excess fuel consumption. Also shown in the example table are the reductions in the hourly totals resulting from signal removal and replacement by 2-way stop control and transformations of these differences into per vheicle values (i.e., delay per vehicle, stops per vehicle or stop probability, and excess fuel per vehicle).

Since the nomographs are based on computations made using the Swedish Capacity Manual methodology for estimating stops and delays, the results are highly similar to the case examples from the research data base and from Terre Haute intersections given earlier in the chapter. Slightly greater variation, but still within quite narrow bounds, is apparent in the examples of nomograph estimates. The ranges of reductions in the four traffic flow related variables are summarized in Table 23.

Intersection Type	Figure Numbers	Traffic Volumes, vph: Main Road Total	Traffic Volumes, vph: Side Road per Approach	Traffic Volumes, vph: Total Intersection	Idling Delay: Signal veh. hrs./hr.	Idling Delay: 2-Way Stop veh. hrs./hr.	Idling Delay: Diff. veh. hrs./hr.	Idling Delay: Diff. per veh. sec./veh.	Total Delay: Signal veh. hrs./hr.	Total Delay: 2-Way Stop veh. hrs./hr.	Total Delay: Diff. veh. hrs./hr.	Total Delay: Diff. per veh. sec./veh.
4-Way, 2 Lane Major, 2 Lane Minor.	7	750	125	1,000	2.2	0.5	1.7	6.1	4.4	1.5	2.9	10.4
4-Way, 4 Lane Major, 2 Lane Minor.	11	1,000	175	1,350	3.2	1.3	1.9	5.1	6.4	2.5	3.9	10.4
4-Way, 4 Lane Major, 4 Lane Minor.	15	500	100	700	1.2	0.2	1.0	5.1	3.0	1.0	2.0	10.3
T-Intersection 2 Lane Major, 2 Lane Minor.	9	750	125	875	1.9	0.3	1.6	6.6	3.5	0.7	2.8	11.5
T-Intersection 4 Lane Major, 2 Lane Minor.	13	1,000	175	1,175	2.7	0.8	1.9	5.8	5.3	1.2	4.1	12.6
T-Intersection 4 Lane Major, 4 Lane Minor.	17	500	100	600	1.2	0.2	1.0	6.0	2.7	0.5	2.2	13.2

Table 21. Examples Of Nomograph Estimates Of Delay

Intersection Type	Figure Numbers	Traffic Volumes, vph			Stops				Excess Fuel Consumption			
		Main Road Total	Side Road per Approach	Total Intersection	Signal Stops/ hr.	2-Way Stop Stops/ hr.	Diff. Stops/ hr.	Diff. in Stops/ veh.	Signal gal/ hr.	2-Way Stop gal/ hr.	Diff. gal/ hr.	Diff. per veh. gal/ veh.
4-Way, 2 Lane Major, 2 Lane Minor.	8	750	125	1,000	540	270	270	0.27	3.7	1.5	2.2	0.0022
4-Way, 4 Lane Major, 2 Lane Minor.	12	1,000	175	1,350	780	380	400	0.30	5.2	2.5	2.7	0.0020
4-Way, 4 Lane Major, 4 Lane Minor.	16	500	100	700	380	210	170	0.[illegible]	2.3	1.0	1.3	0.0019
T-Intersection 2 Lane Major, 2 Lane Minor.	10	750	125	875	450	140	310	0.35	3.0	0.8	2.2	0.0025
T-Intersection 4 Lane Major, 2 Lane Minor.	14	1,000	175	1,175	670	200	470	0.40	4.5	1.3	3.2	0.0027
T-Intersection 4 Lane Major, 4 Lane Minor.	18	500	100	600	340	100	240	0.40	2.1	0.6	1.5	0.0025

Table 22. Examples of Nomograph Estimates of Stops and Excess Fuel Consumption

Table 23. Range of Impacts Resulting from Conversion from Signal Control to Two-Way Stop Control

Variable	Range of Reductions Resulting from Conversion from Signal Control to Two-Way Stop Control	
	Four-Way Intersections	T-Intersections
Idling delay, sec. per veh.	5.1 to 6.1	5.8 to 6.6
Total delay, sec. per veh.	10.3 to 10.4	11.5 to 13.2
Stop probability, stop per veh.	0.24 to 0.30	0.35 to 0.40
Excess fuel consumption, gal. per veh.	0.0019 to 0.0022	0.0025 to 0.0027

Note: Based on examples detailed in Tables 21 and 22.

It is noted that for similar volume patterns, the benefits of signal removal and replacement with 2-way (minor road) stop control are slightly greater for T-intersections than for 4-way intersections. This is especially true of reductions in stop probability and excess fuel consumption at T-intersections converted to stop control.

ESTIMATES OF DAILY AND ANNUAL IMPACTS

The next step in the process of estimating signal removal impacts is to translate hourly impacts estimated from the nomographs into daily and annual impacts.

Daily Impacts

Three alternative approaches were considered for computing daily impacts:

1. Make separate nomograph estimates of the impact variables for each of the 24 hours of a typical weekday and sum to obtain the daily total. This method is more detailed than justified because, except possibly during peak hours, the various hours of the day will usually fall in the linear range of the nomographs.

2. Divide the typical weekday into two parts:

- the two peak hours of the day
- the remaining 22 hours of the day

Calculate the average hourly traffic volumes for each of these two sub-sets and use these in the nomographs to obtain corresponding estimates of the impact variables. Then estimate daily impacts as follows:

$$\Delta X_{daily} = 2\Delta X_{2} + 22\Delta X_{22}$$

where:

ΔX_2 = the reduction in an hourly impact variable (e.g., vehicle hours per hour of idling delay) resulting from replacement of signal control with 2-way stop control for the <u>average of the 2 peak hours</u>.

$= X_2$, signal $- X_2$, stop

ΔX_{22} = same as above for the <u>average of the remaining 22 hours</u>.

$= X_{22}$, signal $- X_{22}$, stop

ΔX_{daily} = daily total reduction in the impact variable.

An example of the calculation method is shown in Table 24. A blank worksheet is provided as Appendix E.

This method is believed appropriate in the case of intersections where the peak hour volumes are high enough to be in the non-linear range of the nomographs. For lower volume intersection cases, an even simpler approach can be employed, as indicated below.

3. Calculate the average hourly traffic volumes for the 24 hours of a typical weekday. Use these average hourly volumes to estimate the hourly impact variables from the nomographs and multiply by 24.

$$\Delta X_{daily} = 24\,\Delta X_{24}$$

where:

ΔX_{24} = the reduction in an hourly impact variable resulting from replacement of signal control with 2-way stop control for the average of 24 hours of the day

$= X_{24}$, signal $- X_{24}$, stop

INTERSECTION TYPE: [X] 4-Way [ ] T-Intersection Main Road: [ ] 2 Lane [X] 4 Lane Side Road: [ ] 2 Lane [X] 4 Lane			IDLING DELAY (VEH. HRS.)	TOTAL DELAY (VEH. HRS.)	TOTAL STOPS (VEH. STOPS)	EXCESS FUEL CONSUMPTION (GAL.)
AVERAGE OF THE 2 PEAK HOURS		Signal Control (From Nomographs)	2.3	5.2	680	4.4
Total Main Road Vol. = 1000 Side Road Vol. / Approach = 125 Total Intersection Vol. = 1,250		2 Way Stop Control (From Nomographs)	0.5	1.5	280	1.6
		DIFFERENCE	1.8	3.7	400	2.8
TOTAL OF THE TWO PEAK HOURS	x 2 = 2500	x 2 = DIFFERENCE	x 2 3.6	x 2 7.4	x 2 800	x 2 5.6
AVERAGE OF THE REMAINING 22 HOURS		Signal Control (From Nomographs)	0.8	2.0	270	1.6
Total Main Road Vol. = 400 Side Road Vol./ Approach = 50 Total Intersection Vol. = 500		2 Way Stop Control (From Nomographs)	0.1	0.4	110	0.5
		DIFFERENCE	0.7	1.6	160	1.1
TOTAL OF THE REMAINING 22 HOURS	x 22 = 11,000	x 22 = DIFFERENCE	x 22 15.4	x 22 35.2	x 22 3520	x 22 24.2
24 HOUR TOTAL	2 Hrs.+22 Hrs. = 13,500	2 Hrs.+22 Hrs. = DIFFERENCE	2+22 19.0	2+22 42.6	2+22 4320	2+22 29.8
PER VEHICLE IMPACTS (Divide 24 Hour Differences By 24 Hour Volume)			.0014	.0032	0.32	.0022

TABLE 24 WORKSHEET FOR ESTIMATING DAILY IMPACTS OF SIGNAL REMOVAL AND REPLACEMENT BY TWO WAY STOPS

Or alternatively,

$$\Delta x_{daily} = V_{24\ tot.}\ \Delta x_{24}$$

where:

$V_{24\ tot.}$ = the total 24 hour intersection volume, i.e., the sum of all approach volumes

Δx_{24} = the average reduction <u>per vehicle</u> in an impact variable for the average hour.

For example, if excess fuel consumption is reduced by 0.0022 gallons per vehicle during an average hour of the day and the 24 hour total weekday intersection traffic volume is 8,000 vehicles, then the daily impact is a reduction of:

$$\Delta x_{daily} = 8{,}000 \cdot 0.0022$$

$$\cong 18 \text{ gallons per day.}$$

This third and simplest method can be used for approximations when all of the hourly traffic volumes, including the peak hours, are in the linear range of the nomographs.

Annual Impacts

To estimate <u>annual</u> impacts of signal removal, multiply the daily (i.e., typical weekday) total impacts by the ratio:

$$\frac{\text{Annual total intersection volume}}{\text{Typical weekday 24-hour intersection volume}}$$

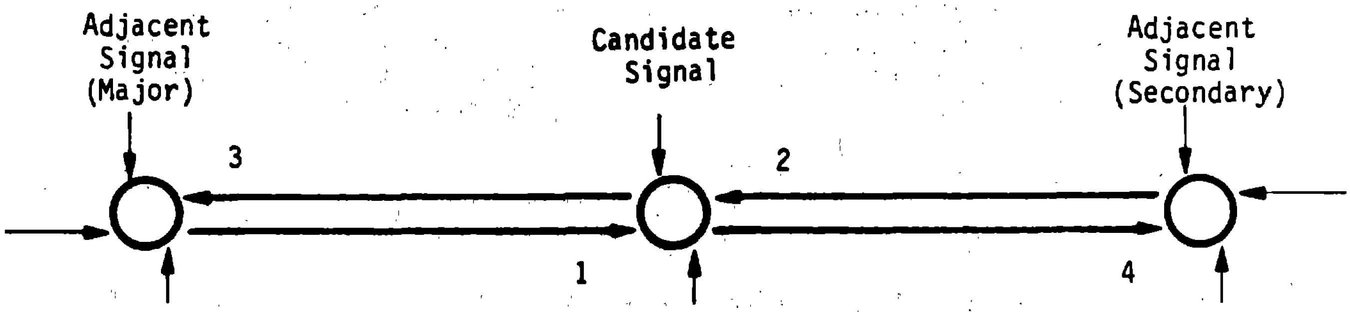
Experience has shown that this factor generally ranges from 310 to 330. Use an average factor of 320 or a unique factor if one has been estimated for your jurisdiction.

EFFECTS OF ADJACENT SIGNALS

All of the foregoing analysis of delays, stops and fuel consumption is based on the assumption that the signal being considered for removal is "isolated" from adjacent signalized intersections. Separation is assumed to be great enough to result in random arrivals rather than cyclical platooned arrivals at the candidate signal. This raises the questions: Would the impacts of signal removal be different if the candidate signal is in a coordinated system with nearby adjacent signals? And by how much? These are difficult questions because in such cases there is a very large number of combinations of variables that could affect the impact of signal removal on delays and stops.

Because the project resources that could be devoted to investigating this question were small, only a limited study could be made. The purpose was not to gain an understanding of all the relationships between the host of variables and signal removal impacts but, rather, to test a sufficient number of conditions to estimate the likely range of possible effects compared with the isolated intersection case.

The general scenario studied was a signal removal candidate intersection located on an arterial between two adjacent signalized intersections, as shown below.



One adjacent signal is assumed to be a "major" crossing and the other a "secondary" crossing with somewhat lower side-street volumes. When the candidate signal is removed it is replaced by two-way stop control.

The existance of the two adjacent signals will have two types of effects when the middle signal is removed, compared with the isolated signal removal case:

1. Delays and stops on the main road approaches to the candidate signal (links 1 and 2 in the diagram) will vary when there are adjacent signals that cause "platooned" arrivals. Usually, with platooned flow, it will be possible to set signal offsets so that traffic performance is better than with random arrivals at an isolated signal -- thus, the signal removal benefits to main road traffic would be less. Sometimes, however, the candidate signal may be located at "just the wrong place", making good signal offsets in both directions impossible, and possibly resulting in greater main road approach delays at the candidate signal than in the isolated signal case.

2. Delays and stops on the main road approaches to the adjacent signals from the direction of the candidate intersection (links 3 and 4 on the diagram) may change when the candidate signal is removed. In the case of

isolated signals (i.e. spacing long enough so that arrivals at adjacent signals are random), removing the middle signal has no effect on traffic arrivals or stops and delays at the other signals. However, when adjacent signals are close enough to result in cyclical platooned arrivals, removing the middle signal _may_ permit better signal offsets between the two remaining outer signals, thereby providing additional signal removal benefits. On the other hand, removing the middle signal may "spread out" the platoons' arrivals at the outer signals due to longer platoon dispersion distances and, if the previous signal offsets (with the candidate signal not removed) were fairly good, delays may actually increase some after signal removal.

The above discussions indicate that it is not certain, _a priori_, that signal removal benefits will be greater or less when adjacent signal effects are accounted for. It will depend on the specific traffic flow, signal timing, and spacing conditions.

Methodology

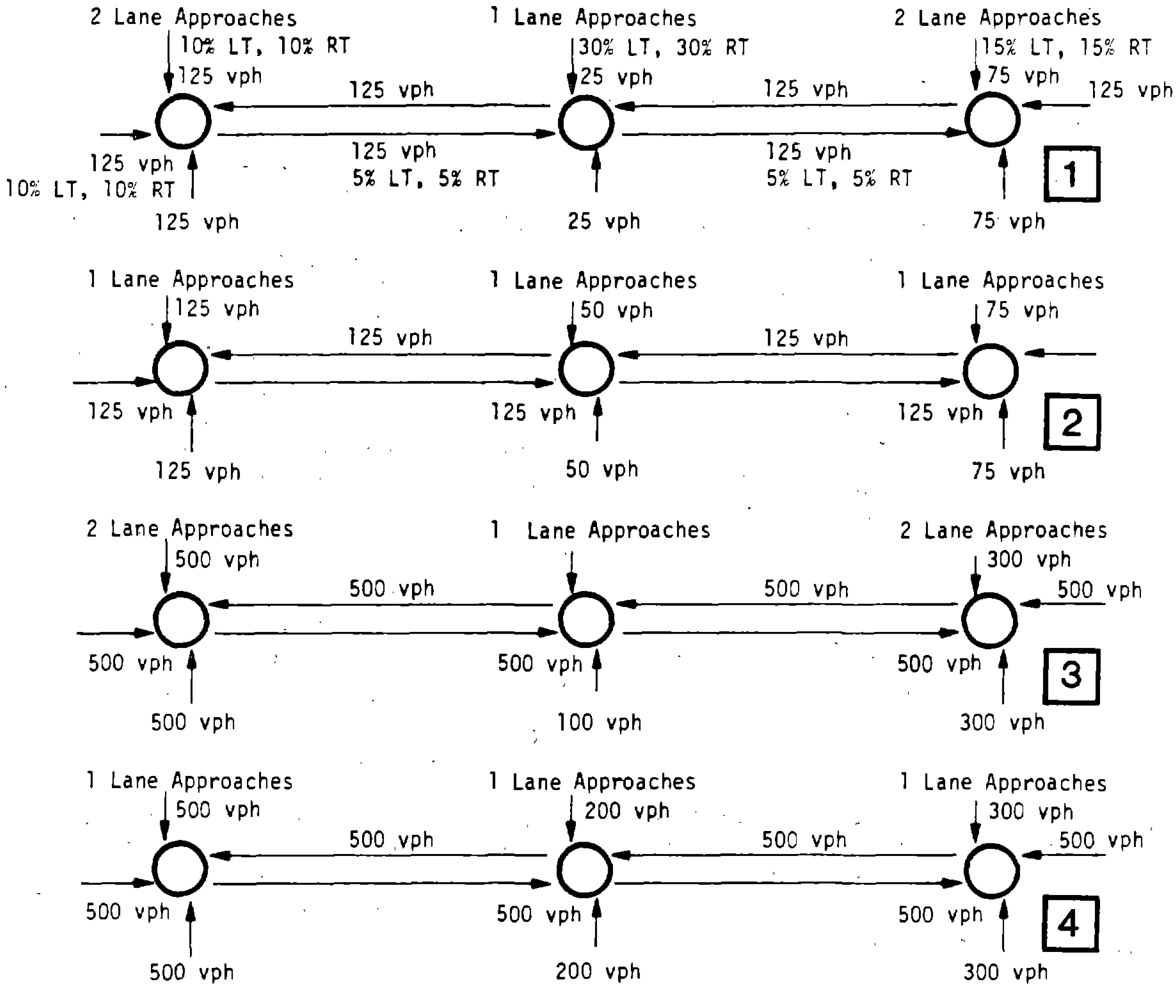
The question of the effects of adjacent signals on signal removal impacts was studied by carrying out a limited simulation experiment using the TRANSYT model (version 7). A total of 36 unique conditions with different traffic volume and signal spacing combinations were tested.

Different levels of the following four variables were incorporated in the experimental design:

- Main road volume -- 2 levels
- Side road volume -- 2 levels for each main road volume level
- Distance between the two outer adjacent signals -- 3 levels
- Relative location of the candidate signal -- 3 levels for each distance.

Figure 19 illustrates the four unique traffic volume combinations studied. Main road total volume is 250 vph in cases 1 and 2 and 1,000 vph in cases 3 and 4. For each main road volume, side road volumes at the candidate (middle) signal are either one-fifth (cases 1 and 3) or two-fifths (cases 2 and 4) of the main road volumes.

At one of the adjacent signals, side-street volumes are equal to main road volume. At the other adjacent signal, side-street volume is six-tenths of main road volume.



Main road has 2 Lane approaches at all signals.
Free Flow speed = 30 mph
Turning percents same for all cases

Figure 19. Traffic Volume Cases Studied (For Adjacent Signal Impacts)

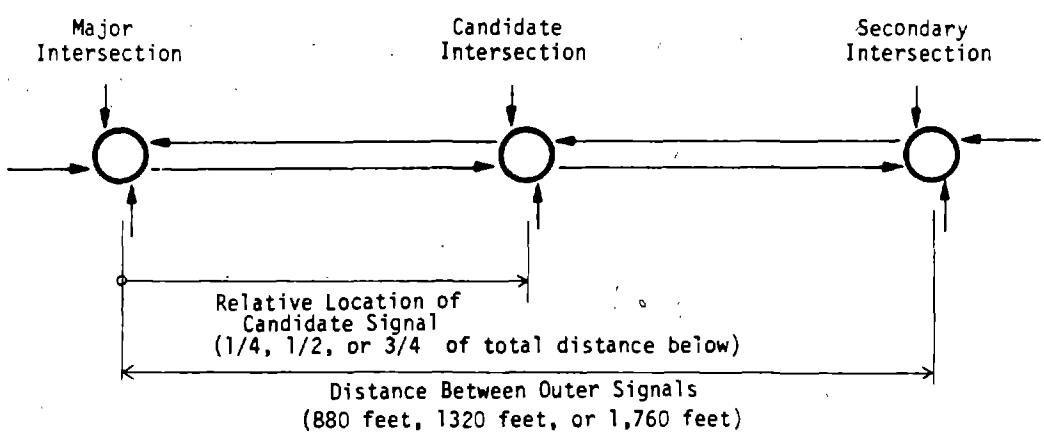


Figure 20. Signal Spacing Alternatives Studied (For Adjacent Signal Impacts)

In cases 1 and 3, the adjacent signal side-streets have 2 lane approaches. In cases 2 and 4 the adjacent signal side-streets have 1 lane approaches. Main road green splits at the outer signals are greater in the former case than the latter case. The above variations and the different levels of crossroad volumes at the candidate signal mean that cases 1 and 3 have more main road green time at each of the three signals than cases 2 and 4.

Spacing between the outer signals was tested at 880 feet (one-sixth mile), 1,320 feet (one-quarter mile), and 1,760 feet (one-third mile). The candidate or middle signal was located one-quarter, one-half, or three-quarters of the distance from the secondary adjacent signal (see Figure 20).

Each of the test conditions was simulated on the TRANSYT model both with and without the candidate signal in place. The case of isolated signals with random arrivals was also tested.

Every TRANSYT test case was made for a 50 second cycle, equal degree of saturation splits at all signals, and TRANSYT optimized signal offsets. Thus, the tests represent traffic performance under a highly refined set of signal timing plans for all cases considered, including the random arrivals (isolated) signals) case and the candidate signal removed case.

It is further assumed, for the low to moderate volume levels characterizing typical signal removal cases, that the side street delay in waiting for an acceptable gap at the stop sign is not appreciably affected by adjacent signals. Earlier research (References 27, 28) has shown that delay at the stop sign is somewhat lower with platooned flow on the main road than with random arrivals. However, this effect is not appreciable until total main road volumes reach 700 to 800 vph -- volume levels that usually would be present only during peak hours at signal removal cases. By calling this factor negligible, the estimated signal removal delay savings may be slightly conservative (i.e. on the low side).

Results

The results of the TRANSYT tests to evaluate the effects on signal removal benefits of adjacent signals are presented in three subsequent tables. These tables contain impacts on intersection delay for the various cases tested. The impacts on stops were very similar to the impacts on delays.

Table 25 summarizes main road idling delay savings per vehicle at the candidate signal resulting from signal removal. Included are delay savings estimates for each test case, for the

Table 25. Main Road Idling Delay Savings at Candidate Signal Resulting from Removal of Candidate Signal, seconds per vehicle.

Distance Between Outer Signals (ft.)	Relative Location of Candidate Signal (ft)	Traffic Volumes at Candidate Signal			
		Total Main Road = 250 v.p.h.		Total Main Road = 1000 v.p.h.	
		Side Road Vol. per Approach		Side Road Vol. per Approach	
		25 v.p.h.	50 v.p.h.	100 v.p.h.	200 v.p.h.
880	220	4.2	5.3	3.1	3.7
	440	2.3	4.5	2.7	5.0
	660	2.9	3.3	2.3	3.5
1320	330	2.6	3.7	2.6	3.9
	660	3.6	5.3	4.0	5.5
	990	2.5	4.0	2.6	4.2
1760	440	2.6	4.3	2.9	4.7
	880	2.6	3.0	3.0	3.7
	1320	2.0	3.5	2.5	4.1
Average for the Above 9 Cases		2.8	4.1	2.9	4.3
Long Spacing Between Adjacent Signals (Random Arrivals)		3.6	6.8	4.2	7.8

average of all those cases, and for the corresponding isolated signal/random arrival case. The results show that delay savings on the main road approaches to the removed signal are usually, but not always, less for the platooned arrival cases than for random arrivals. On the average, the platooned arrival test cases show main road delay savings of 1 to 3 seconds less than the delay savings for the isolated case.

Table 26 summarizes main road idling delay savings at the two adjacent signals resulting from removal of the candidate signal. The only links affected at the adjacent intersections are the "exit" leg links connecting the candidate intersection with each of the two adjacent intersections (i.e. labeled as links 3 and 4 in the diagram on page 83). The table shows that these adjacent intersection approach links have less delay savings in some cases and more delay savings in other cases compared with the isolated signal/random arrivals case. The average effects for the different spacings and volumes tested are very small.

Table 27 is the combination of the two previous tables. It summarizes the main road average delay savings per vehicle at the candidate intersection plus the adjacent intersections. The test cases show that the delay savings resulting from signal removal are slightly less when adjacent signal effects are accounted for than when isolated signal/random arrivals are assumed. On the average, the delay savings are about 40 percent less (i.e. about 1 to 3 seconds less reduction in main road idling delay) than for the isolated signal case. There is a high degree of variability in the individual test cases. The impacts of signal removal at any given location obviously depend heavily on the unique site characteristics including signal spacing, signal timing, and traffic flow characteristics.

All of the preceding analyses has assumed that if the candidate signal is not removed, it will be operated with near optimal signal timing. This assumption means that estimates of signal removal benefits are conservatively low -- i.e. signal delays are likely to be somewhat higher than estimated -- possibly by as much as 15 to 20 percent. This underestimation of benefits at least partially offsets the small overestimation of benefits resulting from not taking adjacent signal effects into account when developing the signal removal impact nomographs.

In the final analysis, unless one knows the specific unique site characteristics of a signal removal candidate intersection and is willing and able to use a simulation tool like the TRANSYT model, the impact nomographs (which were computed assuming no adjacent signal effects) should be reasonably valid for making order of magnitude estimates of signal removal benefits.

Table 26. Main Road Idling Delay Savings at Adjacent Signals Resulting from Removal of Candidate Signal, seconds per vehicle.

Distance Between Outer Signals (ft.)	Relative Location of Candidate Signal (ft)	Traffic Volumes at Candidate Signal			
		Total Main Road = 250 v.p.h.		Total Main Road = 1000 v.p.h.	
		Side Road Vol. per Approach		Side Road Vol. per Approach	
		25 v.p.h.	50 v.p.h.	100 v.p.h.	200 v.p.h.
880	220	-2.0	-2.3	-1.1	0.2
	440	-0.4	1.9	-0.3	2.4
	660	1.1	0.4	0.9	3.6
1320	330	-0.7	-0.7	-0.9	-0.9
	660	0.1	2.2	0.6	1.9
	990	-0.4	-0.4	-0.6	-0.3
1760	440	-0.9	-0.7	-0.9	-0.7
	880	-0.3	-1.7	-0.2	-2.1
	1320	-0.3	-0.3	-0.7	-0.3
Average for the Above 9 Cases		-0.4	-0.2	-0.4	+0.4
Long Spacing Between Adjacent Signals (Random Arrivals)		0*	0*	0*	0*

*Note: With long signal spacing and random main road arrivals, removal of candidate signal has no effect on delays at adjacent signals. Minus signs mean there is "negative" savings in delay at adjacent signals (i.e. an increase).

Table 27. Main Road Delay Savings at Candidate Signal and Adjacent Signals Resulting from Removal of Candidate Signal, seconds per vehicle.

Distance Between Outer Signals (ft.)	Relative Location of Candidate Signal (ft)	Traffic Volumes at Candidate Signal			
		Total Main Road = 250 v.p.h.		Total Main Road = 1000 v.p.h.	
		Side Road Vol. per Approach		Side Road Vol. per Approach	
		25 v.p.h.	50 v.p.h.	100 v.p.h.	200 v.p.h.
880	220	2.1	2.9	2.0	3.9
	440	1.9	6.3	2.3	7.5
	660	3.9	3.7	3.2	7.1
1320	330	1.9	3.1	1.7	3.1
	660	3.7	7.5	4.5	7.4
	990	2.0	3.6	1.9	4.0
1760	440	1.7	3.6	2.0	4.1
	880	2.3	1.3	2.8	1.6
	1320	1.6	3.3	1.8	3.9
Average for the Above 9 Cases		2.3	3.9	2.5	4.7
Long Spacing Between Adjacent Signals (Random Arrivals)		3.6	6.8	4.2	7.8

CHAPTER VII

COST IMPACTS

Another element to be considered in signal removal is the costs of continued signal operation as compared to the costs of removing the signal and installing and maintaining stop signs at an intersection. Since the costs of operating and maintaining signals are a significant element of a traffic engineering departments' budget, any cost savings from signal removal can be very beneficial and should be considered, along with the other impacts, in developing recommendations for signal removal.

The costs of a continued signal operation include the annual costs of electricity, maintenance, and other operational costs such as signal timing. Additionally, the annualized cost of upgrading the signal display should also be included if it is below design standards or will soon require major investment. The costs of signal removal include the one-time costs of removing the signal hardware and installing stop signs; and the annual cost of maintaining the signs. This chapter discusses these various costs.

COST OF SIGNAL OPERATION

The costs of signal operation and maintenance vary widely between individual intersections and between jurisdictions. The costs are dependent upon a number of factors including the type of signal control; number of signal faces and other hardware; local cost of electricity; the jurisdiction's commitment to maintaining up to date signal timing; and level of effort for routine signal maintenance as well as the amount of emergency maintenance performed. In developing the estimate of the cost impacts of signal removal, it is assumed that most signal installations which are considered for removal will not be complex (generally two or three phase operation) and, at most, standard design. The various costs of continued signal operation are discussed below and summarized in Table 30 (Page 94).

Electrical Costs

Annual power requirements for traffic signals in a number of jurisdictions is summarized in Table 28.

Table 28. Power Requirements of Traffic Signals

JURISDICTION	TYPE CONTROLLER	POWER PER YEAR	COMMENTS
Alexandria, VA	Pre-Timed	2,450 KWH*	Single, 4-way signal head - 8" lens
Alexandria, VA	Pre-Timed	7,480 KWH	8 Signal Faces-8" + 12" lens
Alexandria, VA	Pre-Timed	16,700 KWH	11 Signal Faces - 12" lens
San Francisco, CA	Pre-Timed	12,700 KWH	Reference (22)
West Covina, CA	Pre-Timed	18,900 KWH	Reference (22)

* KWH = Kilowatt Hours

In the West Covina Study, it was found that semi-actuated control required approximately 25% less power than pretimed operation. (Much of this reduction in the power requirements is probably due to the fact that solid-state construction requires less energy than electro-mechanical.)

The cost of this power consumption is obviously dependent on the local rate for energy. Using an energy cost between 2¢ to 3¢ per kilowatt hour, the annual cost of power consumption at signalized intersections generally range from $50 to $550 per intersection. For example, the average annual cost of electricity at signalized intersections in Philadelphia is $250 per intersection.

Maintenance Costs

Table 29 summarizes the ranges of maintenance costs for the various types of signal operation. The estimates made by Tarnoff and Parsonson were based upon the results of a nationwide survey conducted in 1978 to determine the costs incurred by State, county, and municipal traffic engineering organizations for signal system equipment. The KLD cost figures represent the average of the responses to their survey of traffic engineering practices which was conducted as part of the NCHRP 3-20 data collection effort in 1972. The cost figures have been adjusted to account for the effect of inflation (8% annual rate) so as to reflect 1980 costs.

Table 29. Signal Maintenance Costs

Type of Signal Operation	Annual Maintenance Cost per Signalized Intersection		
	Tarnoff & Parsonson (Reference 23)	KLD (Reference 2)	California
Pretimed	$1,586	$740	$600
Semi-Actuated	$1,857-$3,025	$972	
Full-Actuated	$2,264-$3,503	$1,203	$750

Other Operating Costs

Other operating costs such as signal timing are extremely variable. Tarnoff and Parsonson estimates the following annual cost per intersection for reviewing timing:

- Pretimed $48/Year
- Full-Activated $24/Year
- Semi-Activated $24/Year

Costs of Upgrading

If the signal installation being considered for removal is below current design standards, or, if certain hardware elements are in immediate need of replacement, these costs should be included in the total cost of continued signal operation. The cost of upgrading a signal installation may invlove a few thousand dollars if only new signal heads are required. If total redesign of the intersection is required, including the installation of new signals, cable, poles, controller and underground conduit, the cost can easily reach $25,000 and even higher. As with the other signal operational costs, the costs of upgrading a signal are dependent on the conditions at each individual intersection and the design practices of the local jurisdiction.

For purposes of comparison, the cost of upgrading a signal installation is converted to equivalent uniform annual costs by multiplying it by the appropriate capital recovery factor or CRF. Assuming a 15-year functional life for the new hardware and an interest rate of 12%, the CRF is 0.147. Thus, the estimated equivalent uniform annual costs to upgrade a signal installation are as follows for some common work items:

Replace signal heads	\$ 2,500 X 0.147 = \$ 368
Replace controller (pre-timed)	\$ 6,000 X 0.147 = \$ 882
Replace controller (actuated)	\$ 9,200 X 0.147 = \$1,352
Total redesign	\$25,000 X 0.147 = \$3,675

Table 30. Cost Impacts of Continued Signal Operation

Annual Costs Per Intersection	Type of Signal Control		
	Pretimed	Semi-Acuated	Full-Actuated
Electrical	\$ 50-\$ 550	\$ 50-\$ 550	\$ 50-\$ 550
Maintenance	\$600-\$1600	\$750-\$3000	\$750-\$3500
Signal Timing	\$ 48	\$ 24	\$ 24
TOTAL	\$700-\$2200	\$800-\$3570	\$800-\$4075

COSTS OF SIGNAL REMOVAL

The costs of signal removal involve removing the signal hardware and installing stop signs. Estimates of these costs, which are shown in Table 31, were obtained from several sources; including recent contractor's bids for signal work, local jurisdictions, the NCHRP 3-20 survey (2), and a study of sign maintenance in certain States (24).

Table 31. Cost Impacts of Signal Removal

Item	Frequency	Cost	Equivalent Uniform Annual Cost*
Remove Signal Hardware	Once - per intersection	$1,000 - $3,000	$142 - $441
Install Stop Signs	Once - per sign	$50 - $120	$7 - $18
Sign Maintenance	Once - per sign	$5 - $15	$5 - $15

*Note - Analysis period is 15 years and an interest rate of 12%.

COST SAVINGS OF SIGNAL REMOVAL

To emphasize what was stated earlier in this chapter, the costs of signal operation and signal removal vary greatly between individual intersections and are dependent on the amount and type of hardware installed at the intersection. A signalized intersection with several actuated phases, mast arm assembly and a large number of signal faces, is obviously going to cost significantly more to maintain and operate than a simple or substandard design. Accordingly, the cost of removing the signal hardware will also be greater at the high design intersection.

As an example for a "typical" intersection where signal removal may be considered, (e.g. pre-timed control, standard design-8 signal faces) the various costs are broken down as follows:

Cost of Continued Signal Operation

Annual Electrical Costs	=	$250
Annual Maintenance Costs	=	$1100
Annual Timing Costs	=	$50
TOTAL	=	$1400

Cost of Signal Removal (Equivalent Annual Costs)

Remove Signal	=	$295
Install 2 Stop Signs	=	$ 25
Sign Maintenance	=	$ 20
TOTAL	=	$340

Thus, for this typical case, the annual savings of signal removal are $1,060/year (equivalent annual costs). If this intersection required a new pre-timed controller and new signal heads, an additional $1,250/year would be saved for a total savings of $2,310/year (equivalent annual costs).

Another way of analyzing the cost savings from signal removal is to determine the amount of time that is required for the savings in annual signal operating and maintenance costs to equal the one-time, total costs of removing the signal. For the "typical" intersection case (no upgrading required), the actual one-time, cost of removing the signal and installing stops signs is $2,180. Thus, in this case and probably in most cases the pay-back period is between one and two years.

CHAPTER VIII

ANALYSIS OF UNSUCCESSFUL SIGNAL REMOVAL ATTEMPTS

This chapter covers the results of an investigation of intersections at which unsuccessful attempts were made to remove signals. Unsuccessful signal removal attempts are defined to include two cases:

1. The traffic engineer's recommendation to remove the signal was never implemented.

2. The signal was "removed" (i.e., the signal was placed in the interim control mode or signal operation was actually discontinued and replaced by stop control) but within a short time period, ranging from a few days to several weeks, signal control was reinstituted.

The data base contained 46 intersections at which signal removal attempts were unsuccessful. The characteristics of these intersections were analyzed to determine if they were characterized by frequently recurring special conditions. Also, comparisons were made of the physical and traffic characteristics of the 46 intersections where removal attempts were unsuccessful and the main data set of 191 urban intersections where signals were successfully removed in order to identify any significant differentiating factors.

REASONS FOR FAILURE

At 41 of the 46 intersections where signal removal attempts failed, the reason cited was strong public opposition. This opposition was expressed in the form of phone calls, letters and petitions to the traffic engineer and the city council from residents and business in the immediate locale of the intersection. In a few cases, complaints were received from parents of school children even though the signals in question were not in close proximity to schools. At one location, the opposition to signal removal came from transit operators that used the signal to turn onto the major street.

The complaints usually concentrated on a perceived safety problem that would exist if the signal was removed. The safety problems mentioned most frequently included an increase in accidents, traffic fatalities, high speeds, and difficulty for pedestrians, (particularly elderly people) in crossing the street.

Signal removal attempts were unsuccessful at the other five intersections for technical reasons including increases in accidents during the interim control period and an increase in side-street vehicular delay due to capacity constraints downstream of the intersection on the major street.

RECURRING SPECIAL CONDITIONS

The review of the intersections where signal removal attempts were unsuccessful indicated two major recurring conditions:

- Signals located at major traffic generators especially employment sites) where sharp peaks occur during commuting periods and problems in crossing or entering the main road are perceived for these short periods.

- Signals located near special generators which generate either substantial volumes or special categories of pedestrian traffic as perceived by those opposing removal (e.g., schools, libraries, homes for the elderly, hospitals, etc.)

OTHER FACTORS DIFFERENTIATING SUCCESSFUL AND UNSUCCESSFUL SIGNAL REMOVALS

Intersection Geometrics

Intersections with "non-standard" geometrics were over-represented in the unsuccessful signal removal data set. Twelve percent of the intersections where signal removal attempts failed had offset approaches as compared to 5.3 percent of the successful signal removal attempts. Similarly, 36 percent of the unsuccessful signal removal attempts involved intersections with an angle of crossing of less than 90° as compared to 19 percent of those intersections where signal removal was successful.

Traffic Volumes

Traffic volumes were generally higher at those intersections where signal removal failed. The average peak hour entering volume at these intersections was approximately 1200 vph, nearly 300 vph higher than the peak-hour volumes entering the intersections where signals were successfully removed. This additional traffic volume was due to heavier traffic on the major street rather than higher side-street volumes. An indication of this is the percent of intersections in each group that satisfied the minimum volumes of Warrant #2 (Interruption Warrant) for at least one hour. As discussed previously, only 23.2 percent of the successful signal removal attempts satisfied Warrant #2 for at least one hour. On the other hand, 55.5 percent of the unsuccessful removal attempts involved intersections with volumes that satisfied the Interruption Warrant for one or more hours.

SUMMARY

It appears that special site conditions (e.g., special traffic generators, schools, hospitals, libraries) are more accountable than any other factors for unsuccessful signal removal attempts. Next most important as a possible indicator of difficulty in attempting to remove a signal is traffic volume that exceeds the MUTCD Interruption Warrant for one or more hours. Atypical intersection geometry may also be a differentiating factor to which the traffic engineer should be sensitive in contemplating signal removal, although it should be noted that there were more successful removals than unsuccessful attempts at such intersections.

CHAPTER IX

TRAFFIC SIGNAL REMOVAL DECISION PROCESS

Traffic signals enjoy a high status among many segments of the public, elected officials, and public administrators. The popular belief, though often unsupported by evidence, is that signals somehow enhance traffic safety and improve traffic flow conditions. The bias in favor of traffic signals was found to exist in varying degrees in all of the local and state jurisdictions visited. Given this popular bias, the practical reality is that signals are considerably harder to remove than to install. This is a reality that cannot be changed simply by instituting an objective set of signal removal criteria, but one that can only undergo gradual transformations as more complete data on signal removal impacts becomes available. Consequently, in order to be of practical use to traffic engineers, signal removal criteria have to be more stringent than signal installation warrants.

In keeping with the practical realities cited above, the proposed approach to signal removal justification is a sequential screening process in which a series of criteria must all be satisfied before signal removal is recommended. This approach differs markedly from the signal installation justification process in which only one criterion from a set of alternatives must be satisfied.

The signal removal decision is organized as a two-stage process:

- Stage I - Preliminary Screening. This part of the process can be completed fairly quickly once the basic inventory data on intersection conditions have been collected. The purpose of this quick screening is to determine if additional analysis of the intersection is justified.

- Stage II - Detailed Analysis. This is a more time consuming process which is pursued only if the candidate intersection survives the screening process. The analysis includes predicting the change in accidents, computing other impacts of signal removal canvassing the general strength of signal removal opposition, and finally making the decision whether or not to remove the signal.

The following sections detail the procedures utilized in each of these two stages.

STAGE I - PRELIMINARY SCREENING

Figure 21 illustrates the structure of the preliminary screening process. The first step of the process is to make an inventory of current conditions at the intersection. The specific data required to perform the signal removal analysis are as follows:

- Intersection geometrics (e.g., number of lanes/approach)
- Side-street sight distance
- The number of vehicles entering the intersection in each hour from each approach during a representative day
- Accident experience at the intersection (total number of accidents) for at least one year

Depending on site-specific conditions, additional data, such as major street speeds, heavy turning movements, pedestrian counts, etc. may also be necessary. After the intersecition data is obtained a series of criteria are considered, each of which must be satisfied in order for the intersection to survive the screening. Namely:

1. Sight Distance Adequacy?

   Is the sight distance for side street drivers adequate for them to observe acceptable gaps in the main road traffic stream in the event the signal is replaced by stop sign control? If the sight distance is less than the minimum values recommended in the Transportation and Traffic Engineering Handbook (26), the signal should be retained. (See Table 32). If limited sight distance is caused by an easily removed obstruction (e.g., overgrown foliage), or a multi-way stop control is planned after signal removal, consider this criterion satisfied and proceed to next step in the screening process.

2. Special Site Conditions?

   Do special site conditions make signal removal institutionally infeasible? The review of the intersections where signal removal attempts were unsuccessful indicated only two major recurring conditions:

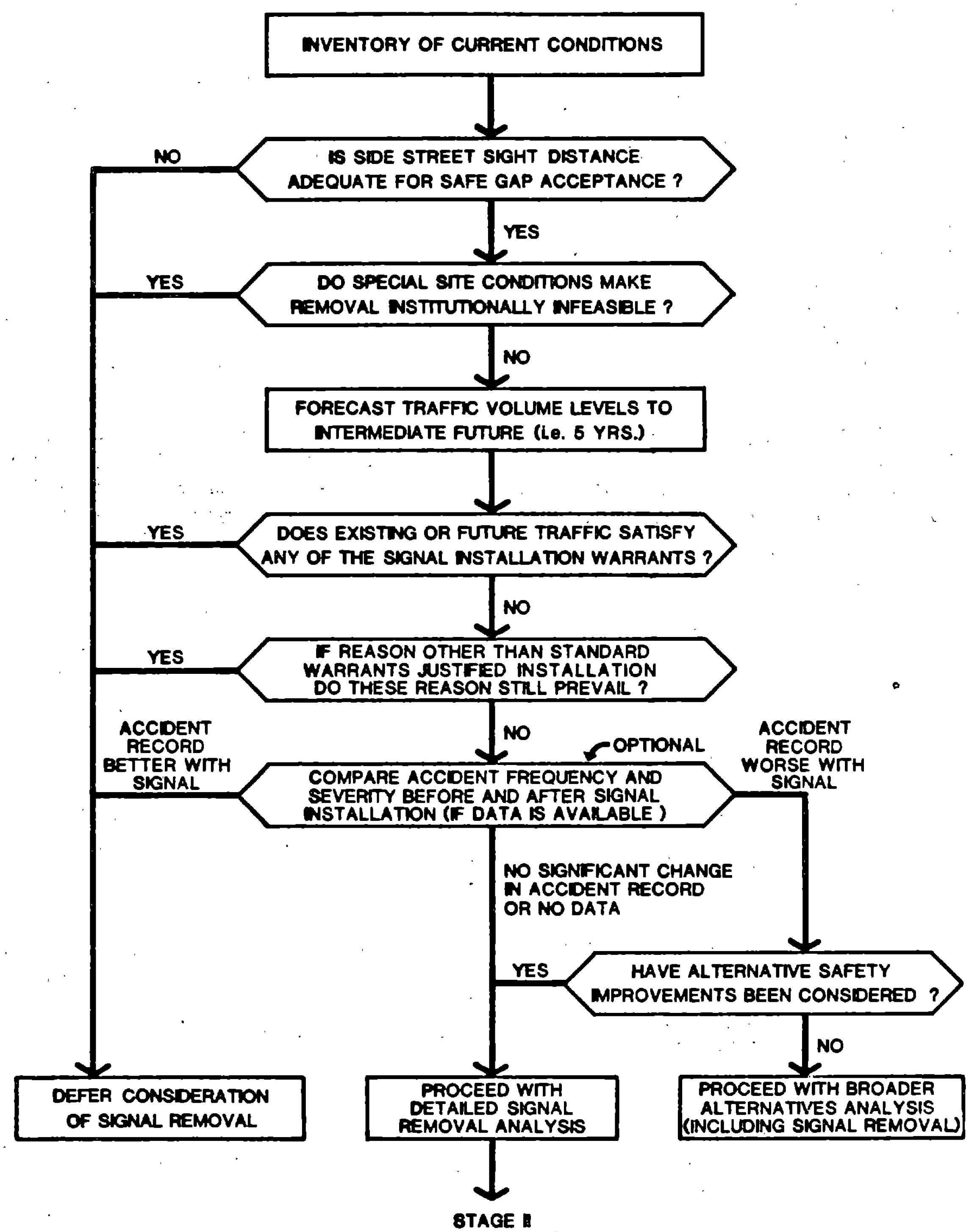


Figure 21. Signal Removal Decision Process
Stage I - Preliminary Screening

Table 32. Suggested Corner Sight Distance At Intersections.

Design Speed	- MPH (KPH)	20 (32)	30 (48)	40 (64)
Minimum Side Street Distance*	- ft (m)	200 (61)	300 (91)	400 (122)

*Corner sight distance measured from a point of the minor road at least 15 feet (4.6 m) from the edge of the major road pavement and measured from a height of eye of 3.75 ft. (1.1 m) on the minor road to a height of object of 4.5 ft. (1.4 m) on the major road.

Source: Baerwald, J. E. (ed.), Transportation and Traffic Engineering Handbook, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, pg. 613, 1976 (Ref. 26)

- Signals located at major traffic generators (especially employment sites) where sharp peaks occur during commuting periods and problems in crossing or entering the main road are perceived for these short periods.
- Signals located near special generators which generate either substantial or special categories of pedestrian traffic as perceived by those opposing removal (e.g., schools, libraries, homes for the elderly, hospitals, etc).

At these locations it is best to first discuss the proposed removal with the affected employment site, school or neighborhood association prior to making any in-depth studies.

3. Signal Installation Warrants Met?

Are any of the standard signal installation warrants satisfied by either current or intermediate term or future traffic volumes?

4. Special Justifications?

If reasons other than the standard warrants were used to justify the signal installation, do these reasons still prevail? There are undoubtedly, cases where unwarranted signals have been installed as a result of pressure from a small special interest group based on reasons which either are no longer perceived as problems or can be shown to be invalid.

5. Accident Changes After Signal Installation? (Optional Criterion)

Were accident frequency and severity levels significantly worse after signals were installed than before? This is an optional criterion which should only be used when the signal installation is relatively recent (e.g., five to ten years old), where adequate accident data are available, and where traffic volumes have not changed substantially during the life of the signal.

6. Alternative Improvements Considered?

If accident problems were significantly worse after signal installation than before, have alternative safety improvements been fully considered? Examples of alternative actions to consider in lieu of signal removal include:

- signal display upgrading
- signal clearance interval lengthening (using all red periods)
- signal offset improvements to achieve smoother flow and reduction of stops
- double cycling of signal timing to reduce the number of side street greens per hour
- semi-actuation or full actuation
- shortening of average side street green intervals through pedestrian actuation
- installation of advance warning devices
- improving pavement friction

- turn prohibitions
- parking prohibitions
- removal of site obstructions
- improved geometric design features, etc.

If such alternatives have not been considered, then their potential and relative costs should be investigated as possible alternatives to signal removal.

STAGE II - DETAILED ANALYSIS

This is a more time consuming analysis process which is pursued only if the candidate intersection survives the preliminary screening process. At this time a preliminary decision should be made concerning the type of sign control that is to be installed after the signal is removed--namely, either two-way stop or multi-way stop. This decision is a local matter and should be based on a number of factors including the current multi-way stop sign warrant contained in the MUTCD, the type of stop control used at adjacent intersections, the local policy and procedures for signing intersections, and engineering judgement. In the event the traffic engineer is unsure of the "best" type of sign control to install, the signal removal impacts should be calculated for both the two-way and multi-way cases. A final decision can be made based on these predicted impacts.

Figure 22 presents the framework for the more detailed stage of the traffic signal removal decision process. The steps contained in the detailed analysis are designed to allow the traffic engineer to predict the impacts that will result from the removal of the traffic signal at a particular intersection. Knowledge of these impacts forms the technical basis for the final decision to remove or not remove the signal. The steps in the detailed analysis are as follows:

1. Accident Impacts

The predicted changes in the annual accident frequency resulting from signal removal is calculated. If the signal is to be replaced with two-way stop control, the following equation is used:

$$Y = 1.01 + .139\ X_1 - .605\ X_2$$

where: Y = change in average annual accident frequency resulting from the removal of a signal and installation of two-way stop control

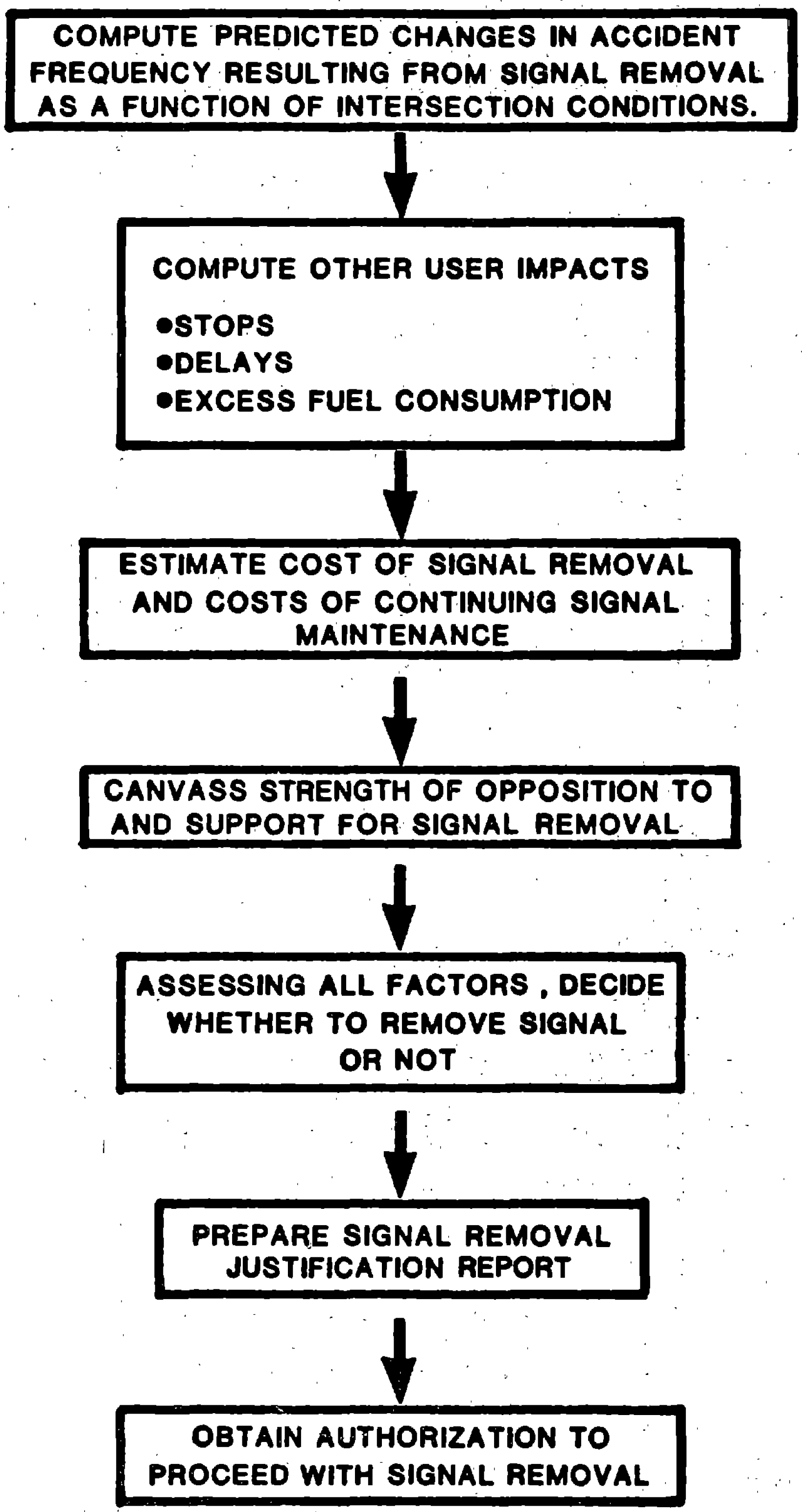


Figure 22. Signal Removal Decision Process
Stage II - Detailed Analysis

X_1 = Volume magnitude as measured by the number of hours per day when traffic volumes satisfy at least 60 percent of the signal installation volume warrant (MUTCD Warrant #1).

X_2 = Average annual accident frequency at the intersection under signal control.

If multi-way stop control is planned after removal of the signal, a decrease in accidents can generally be expected as was discussed in chapter V. It must be emphasized that this predicted decrease is valid only if the intersection possesses the following characteristics:

- low volumes (less than 800 entering vehicles during peak hour)
- relatively balanced flows (ratio of major street volume/side street volume < 3.0)

2. Traffic Flow Related Impacts

Compute estimate of other impacts of signal removal which are related to improved traffic flow efficiency, i.e., intersection stops and delays and derivative impacts on energy consumption. Methods for doing this were discussed and presented in chapter VI.

3. Jurisdiction-Related Costs

Estimate the costs of continued signal operation as compared to the costs of signal removal. The costs of a continued signal operation include the annual costs of maintenance, electricity, and other operational costs such as signal timing. Additionally, the cost of upgrading the signal display may also be included if it is below design standards. The costs of signal removal include the one-time costs of removing the signal hardware and installing stop-signs; and the annual cost of maintaining the signs.

4. <u>Canvass Public Opposition</u>

Assess the relative strength of opposition to, or support for, the proposed signal removal. This is a consideration that begins here and continues even after the decision to remove a signal has been made. Initially, at this stage of the decision process, the local councilperson, neighborhood and business leaders and/or police can be contacted for their opinions. This initial canvassing provides a general idea of the opposition that may be expected during the interim control period and/or at council meetings. This item is pursued further during the public notification which is discussed in the next chapter.

5. <u>Signal Removal Decision</u>

All of the above findings are then weighed by the traffic engineer and the decision is made whether or not to remove (or recommend removal of) the traffic signal. It is neither possible nor desirable to avoid a significant amount of professional judgment in this final decision. In most cases, a number of institutional constraints must also be considered. However, the technical findings from the detailed analysis should provide a strong factual basis for reaching, supporting, and defending the final decision or recommendation.

All of the findings of the decision process would be summarized by the traffic engineer in a signal removal justification report for use in gaining necessary authorizations to proceed.

DISCUSSION

The two stages that comprise the traffic signal removal decision process are very distinct and different. The first stage, or preliminary screening, is made up of a set of criteria with each individual criterion involving a go/no-go decision concerning signal removal. If a signalized intersection survives this preliminary screening, then the second stage, or detailed analysis, is pursued.

The detailed analysis does not involve actual criteria, but is instead a process for estimating the major technical and institutional impacts of removing a traffic signal--namely accidents, fuel consumption, jurisdiction-related costs, and public opposition.

No decision is made concerning traffic signal removal until the last steps of this process after all of the impacts have been estimated and weighed by the traffic engineer.

Under normal circumstances, it is assumed that a traffic engineer will not remove a signal if an increase in accidents and/or a large amount of strong opposition is predicted. However, in the event a jurisdiction is undergoing a budgetary crisis or a severe fuel shortage, the reductions in jurisdiction costs and excess fuel consumption may be weighed more heavily and, as a result, the traffic engineer may be willing to accept a predicted small increase in accidents. It is once again emphasized that the final decision concerning signal removal is a blend of analytical procedures and constitutional/political considerations coupled with professional judgement.

CHAPTER X

DEVELOPMENT OF SIGNAL REMOVAL PROCEDURAL GUIDELINES

Once it has been determined that a traffic signal installation should be removed, orderly procedures are necessary to carry out the actual implementation of the removal of the signal hardware. The primary objectives of the removal procedures are as follows:

- To reduce the hazards associates with driver unawareness of a change in intersection control during the initial transition period; e.g., to reduce the surprise element.

- To convey to the public (including potential opponents) that the signal removal decision was carefully assessed and is likely to result in safety, energy conservation and cost benefits.

The issues involved in these guidelines include advance public information needs, transition or interim control methods, and follow-up information needs. Each issue is discussed separately.

PUBLIC NOTIFICATION

As was discussed in a previous chapter, signal removal has been handled in most jurisdictions on a low keyed basis. A major reason for this is the uncertainty with which traffic engineers have had to face signal removal. No accepted signal removal criteria have been available which has meant that traffic engineers have had to base their decisions on the signal installation warrants as modified by engineering judgement. Additionally, practically no information has been available on the impacts of signal removal, particularly its effect on intersection accidents. Without this kind of information, answering to signal removal opponents whose major argument is safety, can be very difficult. Under these circumstances it is only natural to try to avoid any confrontations.

With sound signal removal criteria that are based on prececent and an accurately predicted improvement in both intersection operations and intersection safety, much of this uncertainty has been done away with. The local traffic engineer now has the necessary facts and technical information with which to counter the arguments of signal removal opponents. In many cases, notifying the public in advance should not jeopardize the chances of a proposed signal removal being successful. Not only is the advance notification important in terms of reducing the surprise element of a change in traffic control device, but public involvement, even in potentially controversial situations, should be a goal of the professional. However, it is also recognized that such goals are easier to discuss in a report than to carry out in the real world environment of time and resource constraints.

Three methods of advance public notification appear to be the most effective in terms of providing the necessary information to the public, particularly those most affected by the removal of a signal. Each one is discussed below:

- Press Release - By being distributed to local newspapers, radio and television stations, this method can provide the widest coverage. The release should include information such as the intersection location, the date and time that the signal is to go into the interim control mode, general reasons that the signal is being removed (e.g., change in traffic flow patterns, closing of nearby generator) and a description of the benefits that will be derived from its removal (reduction in delay, fuel consumption and accidents). The major drawback to the press release is that there is no guarantee that those residents, commercial establishments and drivers most affected by the signal removal will receive information.

- Letter - A letter containing the same information as in the press release can be sent directly to the residents and commercial establishments within the immediate vicinity, say one or two blocks, of the candidate signalized intersection. This ensures that these particular citizens will be notified of the proposed signal removal. Two drawbacks of this method are the time and cost involved in preparing and mailing the letters, and the fact that drivers who utilize the intersection do not receive the information unless they happen to live or work in the immediate vicinity of the intersection.

- Sign - Posting a sign on the intersection approaches is a very effective way of providing notification to both the surrounding residents/commercial establishments and the drivers who use the intersection. A suggested sign for signal removal is shown in Figure 23. Because of limited space, a sign can only provide the information that the signal is going to be removed and the date that the removal is to take place. A description of the benefits that will result from signal removal is obviously not possible with a sign.

To ensure the maximum degree of public notification, the signal removal signs should be posted a few days before the signal is placed in the interim control mode. To supplement the sign, either a letter or press release can be distributed at the same time.

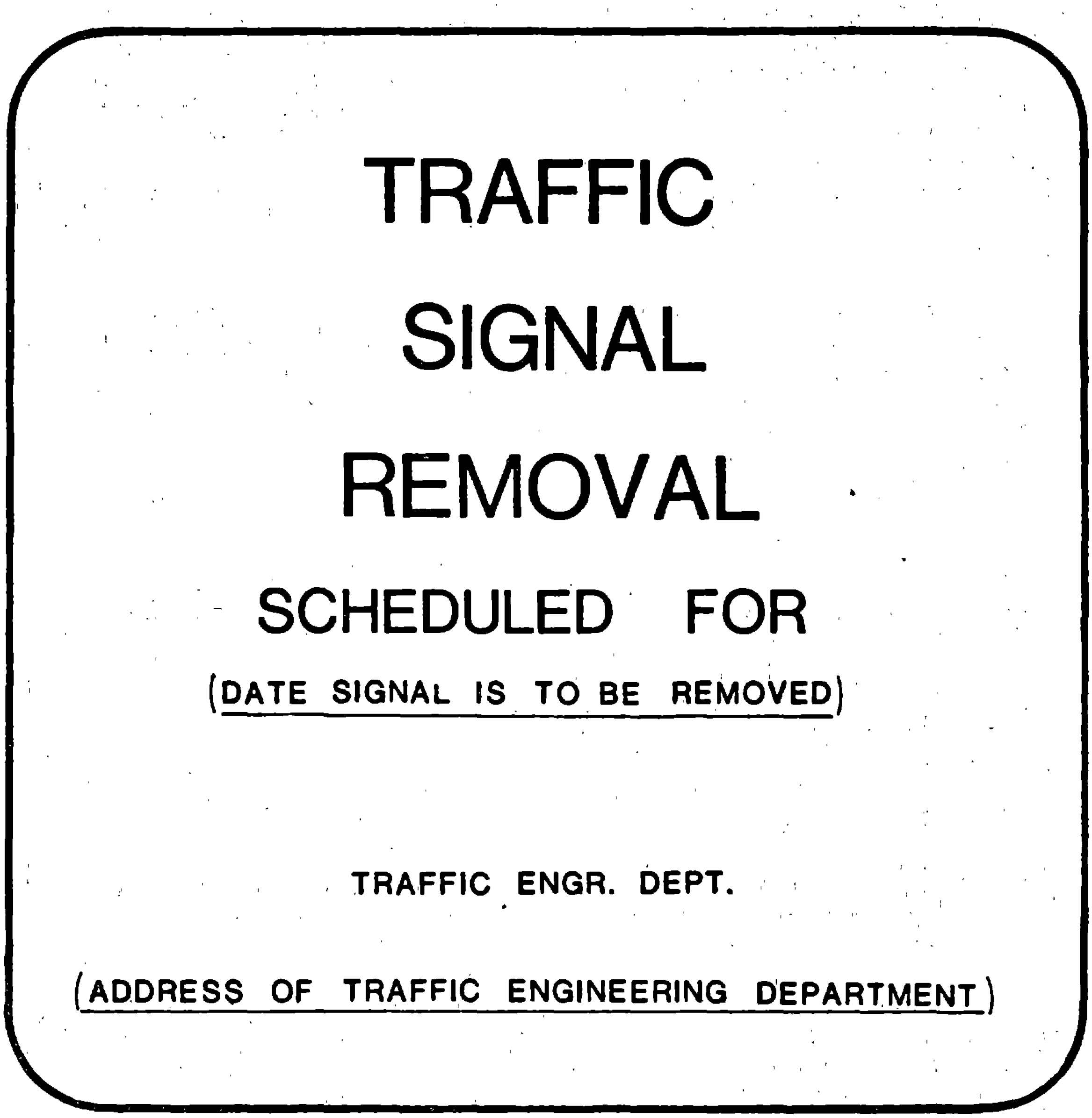


Figure 23. Suggested Signal Removal Sign

It is recognized that the issue of public notification is very much a local matter and is subject to a number of considerations including the local political atmosphere and the existing policies and procedures for notifying and responding to the public. Thus, the above recommendations concerning public notification are general in nature and may require modification to meet specific local needs.

INTERIM CONTROL METHODS

The most widely-used transition methods of changing control devices at an intersection are placing the signal in the flash mode and bagging the signal heads. There is the additional option of providing no transition control at all - simply just removing the traffic signal hardware and installing stop signs. The effectiveness of these three alternative interim control measures was analyzed by comparing the accident experience during the first month of the transition period with the accident experience during the remaining "after" period. The purpose of this analysis was to determine how effective each interim control method was at preparing the driver for the final change in traffic control devices.

The first 30 days of interim control was chosen as the time period for the comparison on the assumption that after the first 30 days, most drivers have had enough time to adjust to the change in the intersection operation and because most of the study jurisdictions used a 30 day interim control period. Only urban intersections converted to two-way stop control were analyzed. The results of this analysis are presented in Table 33.

Table 33. Comparison of Interim Control Measures

Interim Control Measure	Number of Intersections	Difference in Accident Frequency between First Month and Remaining "After" Period
Flash	23	12% Lower During First Month
Bag	25	No Difference
None	62	43% Higher During First Month

When the signals were flashed or bagged there was very little difference in the accident experience between the first month of interim control and the remaining "after" period. This indicates that both of these interim control measures provide for a smooth transition. On the other hand with no transition control the accident experience was 43 percent higher during the first critical month. Although this difference is not statistically significant, it indicates the possibility that a driver adjustment problem does exist and that some sort of interim control measure is required. It is therefore suggested that signals be flashed or bagged for a minimum of 30 days prior to removal.

As to which method of interim control is to be used, it should be noted that in two of the three cities where the signals are bagged, most of removed signals have been far-corner, post mounted installations. In fact, according to the traffic engineer of one of these cities, when the signal removal program was first begun, the signals were flashed and there was an increase in accidents during the interim control period. To counteract this situation, the signals were bagged instead and since then there haven't been any problems.

On the other hand, in most of the jurisdictions that flash the signals prior to removal, the signal installations generally had at least one signal head positioned overhead. Considering the fact flashing beacons are generally overhead installations, it may be that drivers are more comfortable with and use to an overhead flashing signal than one that is post mounted.

There is not sufficient information upon which to base a suggestion concerning the type of interim control method that should be used. Bagging has worked very well on both post mounted and overhead signal installations. Flashing has been very effective with overhead signals and has worked well on post-mounted installations in a number of the study locations. The decision whether to flash the signals or bag the signal heads has to be made by the local traffic engineer based on the predominant type of signal installation, the general driving habits of the public, and engineering judgment. It is essential however, that one of the two modes be used for a minimum of 30 days and that the same method of interim control be used throughout the jurisdiction for consistency.

While the size of the data set on urban signalized intersections converted to multi-way stop control is not large enough to perform the same level of analysis, it does appear that the use of a transition control is not as critical at these locations as it is at two-way stop locations. Nevertheless, for the sake of consistancy, it might be advisable to use the same method of interim control at these locations as well.

Although not used by any of the study jurisdictions, the "Stop Ahead" warning sign may be installed on the stop-controlled approaches to supplement the interim control at the intersection. After the 30 day interim control period when the signal has been removed, it may be advantageous to keep the "Stop Ahead" sign for a few months to emphasize the change in intersection control.

FOLLOW-UP INFORMATION NEEDS

Clearly, because prediction of accidents at individual intersections is not completely accurate, it is important to closely monitor accidents throughout the interim control period. Thus, if not already in existance, a close liaison needs to be developed between the traffic engineering department and the accident records division of the jurisdiction's police department.

An increase in the accident rate during the first critical month is not sufficient reason to abandon the plans for removing the signal. Although if an increase does occur, the signal should remain in the transition control mode for a few more months. If the accident rate is still higher after a few months, an in-depth accident analysis should be performed and retention of the signal should be seriously considered. As part of the accident analysis, other studies such as speeds and delay measurements may prove beneficial.

Accurate accident information should be maintained on all the intersections in the jurisdiction where signals have been removed for at least a few years following signal removal. Assuming that there will be a decrease in accidents at most of these intersections, this kind of "positive" information which is based on intersections within the jurisdiction itself not only lends credibility to the local signal removal progam, but also sets a valuable precedent for additional signal removals.

When it has been determined that the signal hardware can be removed, it may be advisable to remove the signal heads and controller equipment only, and monitor accidents and intersection operations for up to a year prior to removing the remaining hardware. In this way, if the signal needs to be reinstalled due to technical or political reasons, it will not be an expensive endeavor.

SUMMARY

The following signal removal procedural guidelines are suggested:

- Some form of public notification is suggested prior to the removal of the signal. The most effective method is the use of a signal removal sign at the intersection.

- Signals should be flashed or bagged for a minimum of 30 days prior to the signal hardware being removed. If two-way stop control is to be installed after signal removal, the signals should be flashed red-yellow. If four-way stop control is to be installed, the signals should be flashed red-red.

Accidents at the intersection should be monitored very closely during the interim control period. If there is an increase in accidents during this period, the signal should remain in the transition control mode a few more months.

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APPENDIX A

SIGNAL REMOVAL CRITERIA

Successful/Unsuccessful Removal Attempt

Intersection ______________________ City ______________

Type New Control ______________________________

Approach Legs ______________ Angle of Crossing ______________

Major St. Rd. Type ____________ App. Lanes ________ Ex. Left ________

Minor St. Rd. Type ____________ App. Lanes ________ Ex. Left ________

Major St. Speed Limit ________ Minor St. Speed Limit ____________

Minor St. Sight Distance ______________________________

Int. Location ______________ Adjacent Land-use ______________

Nearest Major St. Signals ______________________________

Signal Control Type ______________________________

Signal Display ______________________________

Phases ______________

VOLUMES	Major Street (Both Approaches)	% Left	Minor Street (Highest Single Approach)	% Right
Peak Hr.				
Ave-4 pk. hrs.				
Ave-8 pk. hrs.				
ADT				

PED Volumes (Xing Major St) ______________________________

SIGNAL REMOVAL CRITERIA, cont'd

Date Normal Operation Stopped_______________Date Signal Removed_______________

Adjustment Period Control____

18. <u># Accidents</u>

	Before	After
Rt. Angle		
Rear end		
Turning		
Other		
PD		
Injury		
Fatality		
Total		

19. <u>Special Conditions</u> - schools, change in street network, opposition, etc.

APPENDIX B

ANALYSIS OF RELATIONSHIPS BETWEEN INTERSECTION DESCRIPTORS AND ACCIDENT IMPACTS

The accident impacts present a most challenging analysis problem. Accidents are relatively rare events, and the causation factors are wide ranging, complex and go beyond a simple signal/no signal dichotomy. This makes it extremely difficult to predict the accident consequences resulting from individual signal removals. However, due to the political and institutional nature of traffic signal removal and the general consensus of may people that the traffic signal is a safety device, the development of sound signal removal criteria must include an understanding of the accident impacts of signal removal In ths appendix, the analytical approach used to identify intersection characteristics which are strongly associated with changes in accident experience after signal removal is discussed and the results of the analysis are presented.

ANALYSIS APPROACH

The initial step of the analysis was to divide the date set of urban intersections converted to two-way stop control into the following three subsets describing the accident experience at each intersection following signal removal:

- Increase in Accident Frequency: ΔAccidents $\geqslant +1$
- Little Change in Accident Frequency: $-1 < \Delta$Accidents $< +1$
- Decrease in Accident Frequency: ΔAcidents $\leqslant -1$

For each of the three accident outcome subsets, the distributions of each of a wide variety of intersection condition descriptors were compiled.

The same data set was also divided into the following three subsets describing the injury accident experience following signal removal:

- Increase in Injury Accident Frequency: $\Delta > 0$
- No Change in Injury Accident Frequency: $\Delta = 0$
- Decrease in Injury Accident Frequency: $\Delta < 0$

Frequency classification tables were then computed foı a number of intersection variables as was done earlier for differences in overall accident frequency.

The classification tables for total accident frequency were used to identify which intersection descriptors are significantly different across the accident outcome subsets thereby narrowing down the long initial list of variables to a manageable number for use in the signal removal criteria. The Chi-square test was utilized to determine if accident outcome was dependent on a particular intersection condition descriptor or if the two variables were independent. The Chi-square value for each matrix was calculated as follows:

$$X^2 = \sum_{i=1}^{k} \left(\frac{f_i^2}{F_i}\right) - N$$

Where X^2 = chi-square value
f_i = the actual frequency in the i^{th} cell
F_i = the expected frequency in the i^{th} cell (assuming accident outcome is independent of the intersection descriptor being tested)
k = the number of cells in the matrix
N = the total number of intersections used in the matrix

If the chi-square value was less than the critical chi-square value for $\alpha = .10$, the intersection descriptor was considered not to have a significant effect of the accident outcome following signal removal

One of the customary recommendations in applications of the Chi-square test is that the smallest expectation in any call should be at least 5. Throughout the analysis when this requirement was not met in the oritinal classification and when it was possible neighboring classes were combined until the rule was satisfied. Nevertheless, some of the matrices still did not meet this general rule. Fortunately, for statistical applications, the results of theory sometimes remain substantially true even when some assumptions fail to hold. Thus, it is believed that for those matrices that have only one or two cells with expectations of less than five, using the Chi-square test is still a valid method for determining whether or not an intersection condition descriptor is important. The purpose of this analysis was to isolate which of the intersection descriptors exhibit a strong association with the change in accident experience following signal removal and was not the final statistical analysis. Those variables which were shown to be significant were subjected to further analysis of their relationship to accident impacts.

ANALYSIS OF URBAN INTERSECTIONS (MULTI-WAY STOP CONTROL)

Because of the small amount of data for urban intersections converted to multi-way stop control, frequency classification analysis had to be limited to urban intersections converted to two-way stop control.

ANALYSIS OF URBAN INTERSECTIONS (TWO-WAY STOP CONTROL)

Intersection Layout

Frequency classification matrices were developed for the number of approaches, angles of crossing, number of lanes per major street approach, and number of lanes per side street approach. These matrices are shown in Tables 34 - 37. None of these intersection descriptors show a significant association with the signal removal accident experience. Only 5.3 percent of the study intersections had offset approaches which made it difficult to draw any conclusions concerning this intersection descriptor.

Intersection Sight Distance

Since one of the overall effects of signal removal is a significant increase in right angle accidents and the right angle accident frequency at a stop controlled intersection is affected by the sight distance, it was hypothesized that intersections with limited side street sight distance are more likely to have an increase in accidents after the removal of a signal. The results of the sight distance matrix (Table 38) support this hypothesis in that the differences across the accident outcome subsets are significant ($\alpha = .10$). Of particular interest is that of the study intersections with corner sight distance less than minimum value (300') recommended in the Transportation and Traffic Engineering Handbook (26), over half experienced an increase in the average accident frequency of one or more accidents per year after removal.

Table 38. Relationship Between Side Street Sight Distance and Accident Outcome ($X^2 = 9.44$, Significant at $\alpha = .10$)

Sight Distance	Change in Accident Frequency			Total
	Increase	Little Change	Decrease	
<300	7 (54%)	5 (35%)	1 (27%)	13
300'-600'	18 (35%)	13 (25%)	20 (40%)	51
>600'	11 (27%)	16 (39%)	14 (34%)	41
TOTAL	36 (34%)	34 (33%)	35 (33%)	105

(NOTE - This is one of the few matrices that has a cell size of less than 5. It was decided not to combine sight distance categories and create a single category of "<600'" since 300' is the minimum allowable corner intersection sight distance for a design speed of 30 mph.)

Table 34. Relationship Between Number of Approaches and Accident Outcome (X^2 = 3.2 , Not Significant)

# of Approaches	Change in Accident Frequency			TOTAL *
	Increase	Little Change	Decrease	
3	15 (23%)	24 (37%)	26 (40%)	65
4+	37 (34%)	41 (37%)	32 (28%)	110
TOTAL	52 (30%)	65 (37%)	58 (33%)	175

* The total number of intersections may vary from matrix to matrix depending on the availability of applicable data.

Table 35. Relationship Between Angle of Crossing and Accident Outcome (X^2 = 5.0 , Not Significant)

Angle of Crossing	Change in Accident Frequency			Total
	Increase	Little Change	Decrease	
90°	40 (28%)	58 (41%)	43 (31%)	141
75° - 90	7 (50%)	2 (14%)	5 (36%)	14
$< 75^{\circ}$	5 (25%)	5 (25%)	10 (50%)	20
TOTAL	52 (30%)	65 (37%)	58 (33%)	175

Table 36. Relationship Between # Lanes Per Major Street Approach and Accident Outcome (X^2 = 1.5, not significant)

# Lanes Per Major Street Approach	Change in Accident Frequency			Total
	Increase	Little Change	Decrease	
1	27 (33%)	29 (35%)	26 (32%)	82
2	18 (26%)	28 (41%)	22 (32%)	68
3+	7 (28%)	8 (32%)	10 (40%)	25
TOTAL	52 (30%)	65 (37%)	58 (33%)	175

Table 37. Relationship Between # Lanes Per Side Street Approach and Accident Outcome (X^2 = 3.05, not significant)

# Lanes Per Major Street Approach	Change in Accident Frequency			Total
	Increase	Little Change	Decrease	
1	45 (33%)	48 (35%)	44 (32%)	137
2	7 (18%)	17 (45%)	14 (37%)	38
TOTAL	52 (30%)	65 (37%)	58 (33%)	175

Major Street Operation

Another design feature influencing intersection accidents is the number of conflicts points. For the same side street configuration, a two-way major street has twice the number of conflict points as a one-way major street. Thus, the hypothesis was made that an intersection with a one-way major street will have a better accident experience (e.g., reduction) after signal removal than an intersection with a major street with two-way operation. The results in Table 39 do not support this hypothesis.

Table 39. Relationship Between Major Street Operation and Accident Outcome (X^2 = 4.53, Not Significant)

Major Street Operation	Change in Accident Frequency			Total
	Increase	Little Change	Decrease	
One-Way	9 (35%)	11 (42%)	6 (23%)	26
Two-Way	43 (29%)	54 (36%)	52 (35%)	149
TOTAL	52 (30%)	65 (37%)	58 (33%)	175

Intersection Location

The matrix for distance from nearest major street signal (Table 40) indicates that this variable does not have any strong association with the accident experience after signal removal.

Table 40. Relationship Between Distance from Nearest Major Street Signal and Accident Outcome ($X^2 = 2.44$, Not Significant)

Distance From Nearest Signal	Change in Accident Frequency			Total
	Increase	Little Change	Decrease	
0-600'	20 (31%)	24 (38%)	20 (31%)	64
600'-¼ mi.	14 (33%)	13 (31%)	15 (35%)	42
¼ mile +	5 (22%)	7 (30%)	11 (48%)	23
TOTAL	39 (30%)	44 (34%)	46 (36%)	129

Intersection Operation

Several studies have shown that upgrading the signal display (e.g., mast arms, 12 inch heads, 2 signals/approach etc.) at signalized intersections results in a reduction in accidents. With this is mind, the hypothesis was developed that the removal of a signal at those intersections where the signal layout did not conform with the MUTCD design standards would generally result in better accident experience as compared to the effect of removing the signal at a signalized intersection that was in conformance. The results shown in Table 41 do not support this hypothesis and indicate that the intersection condition descriptor does not exhibit any significant difference relative to the signal removal accident experience. Similarly, the type of signal operation (Table 42) does not explain any of the variation in the differences in accident frequency after signal removal.

Table 41. Relationship Between MUTCD Signal Design Conformance and Accident Outcome (X^2 = 1.49 , Not Significant)

Signal Layout	Change in Accident Frequency			Total
	Increase	Little Change	Decrease	
Conformance	30 (30%)	35 (35%)	34 (34%)	99
Non-Conformance	14 (37%)	15 (39%)	9 (24%)	38
TOTAL	44 (32%)	50 (36%)	43 (32%)	137

Table 42. Relationship Between Signal Operation and Accident Outcome (X^2 = 1.30 , Not Significant)

Signal Operation	Change in Accident Frequency			Total
	Increase	Little Change	Decrease	
Fixed Time	32 (32%)	37 (37%)	30 (30%)	99
Actuated	7 (23%)	11 (37%)	12 (40%)	30
TOTAL	39 (30%)	48 (37%)	42 (33%)	129

Traffic Volumes

From the very beginning of the research, it was felt that the vehicular volume entering an intersection would be a major factor in the development and application of signal removal criteria. Obviously, the more vehicles there are entering an intersection, the greater the exposure to collision. Moreover, higher major road traffic volumes are associated with shorter distributions of gaps for side street vehicles. Additionally, five of the eight MUTCD signal installation warrants utilize intersection volume to some degree.

The hypothesis was developed that intersections with higher traffic volumes will experience a change in accident frequency after signal removal which is worse than at those intersections with lower traffic volumes. The first frequency classification matrix developed for traffic volumes used the entering volume as the variable (Table 43). Not only did this intersection descriptor exhibit no significant association with accident experience following signal removal, but the general trend appears to be just the opposite of what would logically be expected; that is the percentage of intersections experiencing a reduction in accidents after signal removal increases with higher entering volumes instead of decreasing. Similar results occurred when the average of the four peak hours was used. One explanation for these results may be that entering volume is not an adequate measure of potential conflicts between major street and side street vehicles. For example, more conflicts exist at an intersection with a major street volume of 800 vph and side street volume of 200 vph than at an intersection with a major street volume of 950 vph and a side street volume of 50 vph even though the total entering volume is the same for both intersections.

Table 43. Relationship Between Entering Volume and Accident Outcome (X^2 = 7.61, Not Significant)

Entering Volume (Peak Hour)	Change in Accident Frequency			Total
	Increase	Little Change	Decrease	
0-500	7 (29%)	12 (50%)	5 (21%)	24
500-900	20 (33%)	25 (41%)	16 (26%)	61
900-1300	13 (30%)	14 (32%)	17 (39%)	44
1300+	11 (28%)	10 (26%)	18 (46%)	39
TOTAL	51 (31%)	61 (36%)	56 (33%)	168

In order to hopefully account for this situation, the product of the major street volume and higher side street volume at each intersection was used as the volume variable. The product of the conflicting traffic flows has shown to be a useful measure such as in determining the need for exclusive left turn phases. However, as can be seen in Table 44, the matrix of the traffic flow products contains no significant results or discernable trends.

The next volume related intersection descriptor analyzed was the number of hours each intersection satisfied the minimum values of the MUTCD volume warrants. The results for Warrant #1 (Minimum Volume) are shown in Table 45. The results for Warrant #2 (Interruption of Continuous Flow) are shown in Table 46.

Table 44. Relationship Between Product of Major Street Volume x Side Street Volume and Accident Outcome (X^2 = 9.38 , Not Significant)

Product ÷ 100 (Peak Hr.)	Change in Accident Frequency			Total
	Increase	Little Change	Decrease	
0-400	15 (22%)	30 (43%)	24 (35%)	69
400-800	13 (37%)	14 (40%)	8 (23%)	35
800-1200	14 (50%)	8 (29%)	6 (21%)	28
1200+	8 (33%)	7 (29%)	9 (38%)	24
TOTAL	50 (32%)	59 (38%)	47 (30%)	156

Table 45. Relationship Between Warrant Satisfaction and Accident Outcome (MUTCD Warrant #1) (X^2 = 2.54 , Not Significant)

# Hours Warrant #1 Satisfied	Change in Accident Frequency			Total
	Increase	Little Change	Decrease	
0	43 (28%)	59 (39%)	49 (33%)	151
1-2	5 (42%)	3 (25%)	4 (33%)	12
3+	3 (50%)	2 (33%)	1 (17%)	6
TOTAL	51 (30%)	64 (38%)	54 (32%)	169

Table 46. Relationship Between Warrant Satisfaction and Accident Outcome (MUTCD Warrant #2) ($X^2 = 4.24$, Not Significant)

# Hours Warrant #2 Satisfied	Change in Accident Frequency			Total
	Increase	Little Change	Decrease	
0	34 (27%)	52 (42%)	38 (31%)	124
1-2	10 (42%)	5 (21%)	9 (37%)	24
3+	7 (33%)	7 (33%)	7 (33%)	21
TOTAL	51 (30%)	64 (38%)	54 (32%)	169

The number of hours that a signal is warranted under the Interruption Warrant (#2) shows no correlation with the accident experience after removal. On the other hand, the results of the frequency classifiaction matrix for Warrant #1 do differ across the three accident outcome subsets in a logical fashion although the difference is not significant. A major problem with Table 45 is that since very few intersections satisfied the minimum volume warrant for any hours at all, over half of the matrix cells have inadequate number of entrees. In order to obtain a better distribution and thus alleviate this problem, 80 percent and 60 percent of the warrant values were utilized to determine the level of warrant statisfaction at each study intersection. The results are shown in Table 47 and 48.

Table 47. Relationship Between Warrant Satisfaction and Accident Outcome (MUTCD Warrant #1 - 80% Values)
(X^2 = 3.37 , Not Significant)

# Hours Warrant #1 Satisfied (80%)	Change in Accident Frequency			Total
	Increase	Little Change	Decrease	
0	34 (28%)	44 (36%)	43 (36%)	121
1-2	10 (42%)	7 (29%)	7 (29%)	24
3+	7 (47%)	4 (27%)	4 (27%)	15
TOTAL	51 (32%)	55 (34%)	54 (34%)	160

Table 48. Relationship Between Warrant Satisfaction and Accident Outcome (MUTCD Warrant #1 - 60% Values)
(X^2 = 8.2 , Significant at α = .10)

# Hours Warrant #1 Satisfied (60%)	Change in Accident Frequency			Total
	Increase	Little Change	Decrease	
0	18 (23%)	33 (42%)	27 (35%)	78
1-4	21 (38%)	14 (25%)	21 (38%)	56
5+	12 (46%)	8 (31%)	6 (23%)	26
TOTAL	51 (32%)	55 (34%)	54 (34%)	160

It is obvious that this intersection condition description does exhibit some association with the accident outcome after signal removal. While there was not statistical significance for 80 percent values, the results for the 60 percent values were significant at $\alpha = .10$. As another measure of these differences in accident experience, the mean change in the average annual accident frequency was calculated for the various levels of warrant satisfaction (60 percent values). The results are shown in Table 49.

Table 49. Changes in Average Annual Accident Frequency After Signal Removal for Various Levels of Warrant Satisfaction (MUTCD Warrant #1 - 60% Values)

# Hours Warrant Satisfied (60%)	Mean Change	Remarks
0	- .48	Decrease Significant: $\alpha = .025$
1-2	- .14	Change Not Significant
3-4	+ .1	Change Not Significant
5+	+1.85	Increase Significant: $\alpha = .005$

The results of the analysis of intersection volumes indicate that this intersection descriptor should be a significant part of signal removal criteria. The number of hours that an intersection satisfies Warrant #1 or some percentage thereof appears to be a very sensitive volume index in that it takes into account both major street volume, side street volume, and the relationships between the two.

Accidents

The frequency classification matrix for the average annual accident frequency prior to removal is shown in Table 50. Most notable, is that this intersection condition descriptor exhibits a very significant difference ($\alpha = .001$) relative to the signal removal accident experience. The greater the accident frequency before removal, the better chance there is for a reduction in accidents. (It must be remembered however, that most of these signal installations had very low volumes.) This variable is thus a prime candidate for inclusion as one of the intersection condition detectors to be used in the signal removal criteria.

Table 50. Relationship Between "Before" Accident Frequency and Accident Outcome (X^2 = 40.2, Significant at α = .001)

("Before") Average Annual Accident Frequency	Change in Accident Frequency			Total
	Increase	Little Change	Decrease	
0	14 (47%)	16 (53%)	-	30
0-1	12 (31%)	20 (51%)	7 (18%)	39
1-2	12 (29%)	16 (37%)	13 (32%)	41
2-4	9 (25%)	8 (22%)	19 (53%)	36
4+	5 (17%)	5 (17%)	19 (66%)	29
TOTAL	52 (30%)	65 (37%)	58 (33%)	175

The changes of the right angle and rear end accident frequencies after signal removal are significant (See Table 11, page 40). Based on this finding, the assumption was made that an intersection which already had a relatively high right angle accident frequency would experience an increase in accidents after signal removal. Similarly, it was hypothesized that an intersection with a relatively high number of rear end accidents prior to removal would experience a decrease in the overall accident frequency. Frequency classification matrices were constructed for both of these variables which are shown in Tables 51 and 52. Neither of these variables have a significant effect on the accident experience following signal removal.

Injury Accidents

A similar analysis was performed for the change in the number of injury accidents after signal removal. The frequency classification matrices for some of the variables that demonstrated some association with the injury accident experience are shown in Tables 53 through 55. Major street approach speed would have been a useful variable to analyze and its relation to injury accidents. However, since these intersectors were all located in urban areas, there was not a good distribution of speeds. All intersections, except one had a major street speed limit between 20 mph and 35 mph.

The results of the injury accident analysis are very similar to the findings for total accidents, although the differences across the accident outcome subsets are generally not as great. The results for the before period accident frequency and level of warrant satisfaction are statistically significant while the results for sight distance are not significant. Thus, the same intersection condition descriptors can be used for predicting both the number of accidents and severity after signal removal.

SUMMARY

This section described the analysis which was conducted to relate the change in accident frequency and the change in accident severity to a variety of intersection descriptors. The purpose of this analysis was to reduce the number of variables to a few intersection condition descriptors which exhibit a strong association with accident experience following signal removal. The following variables were identified for use in the signal removal criteria.

Table 51. Relationship Between Right Angle Accident Frequency and Accident Outcome
(Includes only those intersections with a total frequency > 0)
(X^2 = 5.6, Not Significant)

Avg. Annual Number of Right Angle Accidents	Change in Accident Frequency			Total
	Increase	Little Change	Decrease	
0	10 (31%)	10 (31%)	12 (38%)	32
0-1	8 (19%)	14 (33%)	21 (49%)	43
1+	10 (36%)	4 (14%)	14 (50%)	28
TOTAL	28 (27%)	28 (27%)	47 (46%)	103

Table 52. Relationship Between Rear End Accident Frequency and Accident Outcome
(Includes only those intersections with a total frequency > 0)
(X^2 = 6.01 , Not Significant)

Avg. Annual Number of Rear End Accidents	Change in Accident Frequency			Total
	Increase	Little Change	Decrease	
0	7 (28%)	10 (40%)	8 (32%)	25
0-1	15 (31%)	13 (27%)	21 (42%)	49
1+	7 (25%)	4 (14%)	17 (61%)	28
TOTAL	29 (28%)	27 (26%)	46 (46%)	102

- Side Street Sight Distance
- Volume (A measure that incorporates both major street volume, side street volume, and their relationships)
- "Before" accident experience.

Table 53. Relationship Between Sight Distance and Injury Accident Outcome
(X^2 = 6.67, Not Significant)

Sight Distance	Change in Injury Accident Frequency			Total
	Increase	No Change	Decrease	
300'	6 (60%)	3 (30%)	1 (10%)	10
300'-600'	10 (23%)	19 (44%)	14 (32%)	43
600'	14 (42%)	10 (30%)	9 (27%)	33
TOTAL	30 (35%)	32 (37%)	24 (28%)	86

Table 54. Relationship Between Warrant Satisfaction and and Injury Accident Outcome
(MUTCD Warrant #1 - 60% Values)
(X^2 = 10.60 , Significant at α = .05)

# Hours Warrant 1 Satisfied (60%)	Change in Injury Accident Frequency			Total
	Increase	No Change	Decrease	
0	19 (27%)	29 (41%)	22 (32%)	70
1-4	12 (27%)	15 (34%)	17 (39%)	44
5-8	14 (61%)	5 (22%)	4 (17%)	23
TOTAL	45 (33%)	49 (36%)	43 (31%)	137

Table 55. Relationship Between "Before" Accident Frequency and Injury Accident Outcome
(X^2 = 30.02 , Significant at α = .001)

Average Annual Accident Freq.	Change in Injury Accident Frequency			Total
	Increase	No Change	Decrease	
0	12 (44%)	15 (56%)	-	27
0-1	9 (26%)	20 (57%)	6 (17%)	35
1-2	11 (33%)	11 (33%)	12 (34%)	34
2-4	6 (23%)	8 (31%)	12 (46%)	26
4+	9 (36%)	3 (12%)	13 (52%)	25
TOTAL	47 (32%)	57 (39%)	43 (29%)	147

APPENDIX C

STATISTICAL METHODOLOGY: PAIRED COMPARISON t TEST

The principal statistical methodology used in this study for testing whether accident frequencies changed following conversion from signal control to stop control was the paired comparison t test. The use of a paired comparison test is an appropriate and often-used technique for analyzing before and after conditions in which data are collected from a sample of specific locations. The paired comparison test has several advantages:

- It eliminates the effects of extraneous variables (e.g., differences in intersection design). Each pair is alike in most respects except for the treatment effects (i.e., signal control vs. stop control) we are trying to measure.

- It is not necessary to assume that the variances of the before and after data set are equal. Nor is it necessary to assume that the individual variables (i.e., the before and after accident frequencies) are sampled in a random and independent manner.

The accident variable used for the before (X_{Bi}) and after (X_{Ai}) condition at each intersection was the <u>average annual accident frequency</u>. This measure was selected for two basic reasons:

- The durations of the before and after periods often differed for an individual intersection.

- The durations of before and/or after periods also differed widely for different intersections.

For each intersection in the sample, the change in average annual accident frequency, d_i, following signal removal was computed for each intersection:

$$d_i = X_{Ai} - X_{Bi}$$

The null hypothesis tested was that the population mean values of annual accident frequency before and after signal removal are equal , i.e.:

$$H_o: \mu_A = \mu_B$$

The alternative hypothesis was that the before and after population means are not equal, i.e.:

$$H_A: \mu_A \neq \mu_B$$

The sample data were stratified into a number of subsets prior to testing to reflect important variables such as: urban/rural, two-way stop/all-way stop, and inadequate sight distance. For each subset of paired data, the sample data were used to compute the t statistic:

$$t = \frac{\bar{d} - 0}{S \sqrt{N}}$$

where:

$\bar{d} = \frac{\sum di}{N}$ = the sample mean of d_i

N = sample size (i.e., number of intersections in the subset)

$S = \sqrt{\frac{\sum d_i^2 - (\sum d_i)^2/N}{N-1}}$ = the sample standard deviation of d_i.

This statistic has the student's t distribution with N-1 degrees of freedom.

The null hypothesis of equal before and after means is rejected when the absolute value of t computed from the sample exceeds the tabled value of $t_{1-\frac{1}{2}\alpha}$, N-1.

We used a level of significance, $\alpha = 0.10$. This means that when the null hypothesis was rejected (i.e., when a "significant" difference was found) the probability that the difference was due to chance was 0.10.

Table 56 shows an example of the paired comparison t test computations.

TABLE 56. EXAMPLE OF PAIRED COMPARISON t TEST.

X_{Bi}	X_{Ai}	$d_i = X_{Ai} - X_{Bi}$	d_i^2
1.0	1.3	+ 0.3	0.09
1.2	1.1	- 0.1	0.01
3.2	17.1	+ 13.9	193.21
4.9	12.0	+ 7.1	50.41
2.1	3.4	+ 1.3	1.69
0	3.0	+ 3.0	9.00
1.0	1.0	0	0
2.0	2.7	+ 0.7	0.49
0	5.0	+ 5.0	25.00
1.0	2.0	+ 1.0	1.00
6.5	11.0	+ 4.5	20.25
2.0	0	- 2.0	4.00
0	3.0	+ 3.0	9.00
1.4	1.8	+ 0.4	0.16
4.0	8.5	+ 4.5	20.25

$N = 15 \qquad \sum d_i = +42.6 \qquad \sum d_i^2 = 334.56$

$\bar{d} = \sum d_i/N = +42.6/15 = +2.84$

$$S = \sqrt{\frac{\sum d_i^2 - (\sum d_i)^2/N}{N-1}} = \sqrt{\frac{334.56 - (42.6)^2/15}{14}} = 3.91$$

$$t = \frac{\bar{d} - 0}{S/\sqrt{N}} = \frac{2.84}{3.91/\sqrt{15}} = \boxed{2.81}$$ significant at $\alpha = 0.005$

Note: Sample shown is for urban intersections with inadequate corner sight distance.

APPENDIX D

INTER-OFFICE COMMUNICATION

Date March 22, 1976

TO: Construction, General Services & Maintenance

FROM: Traffic Engineering Division

SUBJECT: Press Release

The following press release is to be released on Tuesday March 23, 1976 at 9:30 AM. If you have any comments or questions, you are asked to contact the Traffic Engineering Division prior to the above time.

"An engineering study has been completed at the intersection of 26th Avenue and Douglas Street to determine if the existing traffic signal is still warranted. Traffic counts, accident experience and engineering judgement were included in this study. Traffic conditions have changed sufficiently enough at this intersection so that the signal is no longer warranted. This was due to the opening of Interstate 480 through Downtown Omaha. The traffic volumne on Douglas Street was much higher when the Interstate gap existed and all eastbound vehicles on Interstate 80 used Douglas Street. The removal of this signal will reduce accidents, vehicle operating costs, delay and maintenance costs for the City. This traffic signal will be turned off on April 7th.

INTERSECTION TYPE Main Road Side Road	☐ 4-Way ☐ T-Intersection ☐ 2 Lane ☐ 4 Lane ☐ 2 Lane ☐ 4 Lane		IDLING DELAY (VEH. HRS.)	TOTAL DELAY (VEH. HRS.)	TOTAL STOPS (VEH. STOPS)	EXCESS FUEL CON-SUMP-TION (GAL.)
AVERAGE OF THE 2 PEAK HOURS		Signal Control (From Nomographs)				
		2 Way Stop Control (From Nomographs)				
Total Main Road Vol. = ______ Side Road Vol. / Approach = ______ Total Intersection Vol. = ______		DIFFERENCE				
TOTAL OF THE TWO PEAK HOURS	x 2 =	x 2 = DIFFERENCE	x 2 ☐	x 2 ☐	x 2 ☐	x 2 ☐
AVERAGE OF THE REMAINING 22 HOURS		Signal Control (From Nomographs)				
		2 Way Stop Control (From Nomographs)				
Total Main Road Vol. = ______ Side Road Vol./ Approach = ______ Total Intersection Vol. = ______		DIFFERENCE				
TOTAL OF THE RE-MAINING 22 HOURS	x 22 =	x 22 = DIFFERENCE	x 22 ☐	x 22 ☐	x 22 ☐	x 22 ☐
24 HOUR TOTAL	2 Hrs.+22 Hrs. =	2 Hrs.+22 Hrs. = DIFFERENCE	2+22 ☐	2+22 ☐	2+22 ☐	2+22 ☐
PER VEHICLE IMPACTS (Divide 24 Hour Differences By 24 Hour Volume)						

WORKSHEET FOR ESTIMATING DAILY IMPACTS OF SIGNAL REMOVAL AND REPLACEMENT BY TWO WAY STOPS

*U.S. GOVERNMENT PRINTING OFFICE: 1980 720-978/98 1-3