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16. Abstract

The TEXAS Model for Intersection Traffic is a microscopic simulation package describing the behavior of individual driver-vehicle units at isolated intersections. This report deals with two applications of this model, namely determining the capacity of an intersection and analysis of warrants for traffic signal control. Service volume has been related quantitatively to five subjectively-defined levels of service by identifying suitable performance indicators, such as average queue delay, percent of vehicles required to stop, and percent of vehicles required to slow to below 16 kph (10 mph). These indicators are computed routinely during the simulation process and can be used for evaluating the performance of existing or proposed unsignalized intersections operating under various traffic volumes and different types of control. In the signal warrant analysis, effectiveness of various types of control is judged on the basis of total cost. This cost includes costs associated with user stopping and delay and costs related to providing, operating, and maintaining traffic control devices. It was concluded that peak-hour traffic volumes which result in unreasonable delay may be used as a criterion for judging the need to replace two-way stop control with signals, while total intersection costs should be considered when replacing all-way stop control with signals. Another finding indicated that fewer vehicles were delayed and that the total costs of controlling and using an intersection were lower under traffic-actuated signal control than under pretimed control.

17. Key Words

microscopic traffic simulation, computer simulation, levels of service, signal warrants, traffic performance indicators, intersection

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by

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Glenn E. Grayson

Research Report Number 184-4F

Simulation of Traffic by a
Step-Through Technique (Applications)

Research Project 3-18-72-184

conducted for

Texas
State Department of Highways and Public Transportation

in cooperation with the
U. S. Department of Transportation
Federal Highway Administration

by the

CENTER FOR HIGHWAY RESEARCH

THE UNIVERSITY OF TEXAS AT AUSTIN

July 1978

There was no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine, manufacture, design or composition of matter, or any new and useful improvement thereof, or any variety of plant which is or may be patentable under the patent laws of the United States of America or any foreign country.

PREFACE

This is the fourth and final report in a series of four reports on Research Study 3-18-72-184, "Simulation of Traffic by a Step-Through Technique." This report describes the applications of the TEXAS Model for Intersection Traffic. The model simulates the behavior of individual driver-vehicle units at isolated intersections. The results of the simulation are analyzed to determine the capacity at various levels of service and to investigate the validity of current warrants for signal control.

The four reports which deal with the development, use, and application of the TEXAS Model are

> Research Report No. 184-1, "The TEXAS Model for Intersection Traffic - Development," Clyde E. Lee, Thomas W. Rioux, and Charlie R. Copeland.
>
> Research Report No. 184-2, "The TEXAS Model for Intersection Traffic - Programmer's Guide," Clyde E. Lee, Thomas W. Rioux, Vivek S. Savur, and Charlie R. Copeland.
>
> Research Report No. 184-3, "The TEXAS Model for Intersection Traffic - User's Guide," Clyde E. Lee, Glenn E. Grayson, Charlie R. Copeland, Jeff W. Miller, Thomas W. Rioux, and Vivek S. Savur.
>
> Research Report No. 184-4F, "Application of the TEXAS Model for Analysis of Intersection Capacity and Evaluation of Traffic Control Warrants," Clyde E. Lee, Vivek S. Savur, and Glenn E. Grayson.

Requests for copies of these reports should be directed to Mr. Phillip L. Wilson, Engineer-Director, Planning and Research Division, File D-10, Texas State Department of Highways and Public Transportation, P. O. Box 5051, Austin, Texas 78763.

ABSTRACT

The TEXAS Model for Intersection Traffic is a microscopic simulation package describing the behavior of individual driver-vehicle units at isolated intersections. This report deals with two applications of this model, namely determining the capacity of an intersection and analysis of warrants for traffic signal control.

Service volume, which is the maximum traffic volume that can be accommodated at an intersection while maintaining a specified level of service, has been related quantitatively to five subjectively-defined levels of service by identifying suitable performance indicators, such as average queue delay, percent of vehicles required to stop, and percent of vehicles required to slow to below 16 kph (10 mph). These indicators are computed routinely during the simulation process and can be used for evaluating the performance of existing or proposed unsignalized intersections operating under various traffic volumes and different types of control.

In the signal warrant analysis, effectiveness of various types of control is judged on the basis of total cost. This cost includes costs associated with user stopping and delay and costs related to providing, operating, and maintaining traffic control devices. Representative values of one cent per vehicle stop and three dollars per hour of vehicle delay are used. It was concluded that peak-hour traffic volumes which result in unreasonable delay may be used as a criterion for judging the need to replace two-way stop control with signals, while total intersection costs should be considered when replacing all-way stop control with signals. Another finding indicated that fewer vehicles were delayed and that the total costs of controlling and using an intersection were lower under traffic-actuated signal control than under pretimed control.

SUMMARY

This report describes practical application of the TEXAS Model for Intersection Traffic to determine capacity and analyze the warrants for signalization of isolated intersections.

Hitherto, the manner of determining capacity has been based on empirical formulae, probability of vehicle spacing, or observation of intersections. The method described in this report utilizes a microscopic demand-response simulation technique for evaluating the performance of intersections with any form of traffic control. The relationship between capacity and level of service is investigated. Performance indicators that can be used to define levels of service at intersections are studied, and appropriate indicators are selected. A relationship between these selected performance indicators and each subjectively-defined level of service is established. Four cases in which the TEXAS Model can be used to evaluate the behavior of an intersection are then outlined.

The working of the TEXAS Model is explained briefly with an example using actual input. The four cases previously mentioned are used to illustrate the method. First, the level of service of a 2-lane by 2-lane uncontrolled intersection is determined to be E when it is accommodating 1600 veh/hr. Then, the maximum volume that can be accommodated if that intersection is to operate under a Level of Service B is determined to be 1000 veh/hr. Next, for that intersection, the level of service for any volume and the service volume at each level of service are analyzed with a graph and a table. Finally, the optimum lane configuration and traffic control scheme to accommodate a desired service volume are designed, and a summary table is constructed in the process.

In the last chapter of the report, an analysis of the traffic conditions which must be met before signalization may be warranted at an intersection is described. Traffic volume and delay statistics computed by the TEXAS Model are analyzed for trends, relationships, and critical conditions and are used to develop data for a cost analysis of various types of intersection control. Warrants for traffic signals as recommended by the Manual on Uniform Traffic

Control Devices and the Texas State Department of Highways and Public Transportation are then analyzed on the basis of cost effectiveness.

Conclusions forwarded as a result of the total investigation include the following.

(1) Two-way stop control provides the least costly means of intersection control over a wide range of traffic conditions when considering costs associated with stopping, delay, and traffic control devices.

(2) All-way stop control cannot be justified solely on the basis of total intersection costs.

(3) For isolated intersections, traffic-actuated signal control is more cost effective than fixed-time signal control.

(4) The decision to replace two-way stop control with signal control should probably be based more on tolerable delay than on total intersection costs.

IMPLEMENTATION STATEMENT

The TEXAS Model for Intersection Traffic is operational on both CDC 6600 and IBM 370 computers and can be used to analyze traffic performance at a single intersection with any conventional form of sign or signal control, or with no traffic control other than the basic rules of the road. This report presents procedures for applying the simulation model to (1) determine intersection service volume at a specified level of service, (2) define the capacity of an intersection approach or of the whole intersection, and (3) evaluate conditions which may warrant a specific form of sign or signal control on a delay or on a cost-effectiveness basis.

It is recommended that traffic engineers and transportation planners utilize the simulation technique and the procedures suggested to determine optimum designs for specific intersection situations. Considerable refinement over conventional analysis techniques is practical for both simple and complex intersection configurations. Extended use of the simulation methodology will lead to improvements in routine intersection design, analysis, and operation.

The quantitative indicators for level of service that are presented in Table 3 should be utilized in evaluating existing intersection performance and in designing new intersections. Required data can be obtained practically, either by field survey or by simulation.

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CHAPTER 1. INTRODUCTION

Traffic flow at street and highway intersections is a complex, time-varying phenomenon that is affected by roadway geometry, driver and vehicle characteristics, traffic controls, and many other less tangible factors. Engineers are faced with the task of designing intersection configurations and selecting appropriate controls which will simultaneously maximize safe traffic throughput and minimize cost, delay, fuel consumption, pollution, vehicle wear and tear, and driver frustration. Estimating the capacity of existing or proposed intersections and deciding upon the most effective type of traffic control for a given situation constitute a major portion of this job. Practical, effective techniques for making these determinations are needed.

Historically, engineers either have relied on judgment developed through experience with similar circumstances to guide their decisions or have applied empirical or probabilistic methods of analysis. Other than direct observation, no means has been available for studying the behavior of individually characterized driver-vehicle units as they operate in the partly static, partly dynamic intersection environment, but recent advances in digital computer technology now make this possible through simulation.

The expected interaction among the four primary elements of intersection traffic flow, (1) the driver, (2) the vehicle, (3) the roadway configuration, and (4) the traffic control, can be evaluated in considerable detail and in a highly-compressed time frame by computer simulation. Precedent reports (Refs 1-3) in this series describe the TEXAS (Traffic EXperimental and Analytical Simulation) Model for Intersection Traffic, a computer simulation package that was developed specifically for analyzing traffic performance at single, multi-leg, mixed-traffic intersections operating either without control devices or with any conventional sign or signal control scheme. In this model, each simulated driver of an individually-characterized vehicle is provided every half second or so with information concerning his current surroundings. Then, on the premise that the driver wants to maintain a desired speed, obey applicable traffic laws, and maintain safety and comfort, the priority choice to (1) continue at the same speed, (2) accelerate, (3) decelerate, or (4) change lanes is made and implemented in the model. Sequential application of this process steps each driver-vehicle unit through the intersection on a microscopic space and time scale and allows performance statistics to be gathered for subsequent analysis. A wide range of intersection configurations, traffic patterns, and control schemes can be examined quickly without the time and expense of field studies or experimental installations.

This report describes an investigation in which the TEXAS Model was applied for analyzing intersection capacity and for evaluating warrants for various forms of traffic control. Pertinent features of the TEXAS Model which make it uniquely suited for these purposes are presented in the next chapter, and in succeeding chapters techniques for using the model as a practical aid to engineering decision making are outlined.

Intersection capacity analysis involves two basic steps: (1) selecting the criteria which define capacity, and (2) estimating the maximum amount of traffic that can be accommodated without violating these criteria. The TEXAS Model permits a wide range of geometric, traffic, and control conditions to be specified, and then after simulating traffic flow for a selected period of time, presents summary statistics concerning the behavior of traffic and of a signal controller if one was used. Comparison of the resulting statistics with the selected capacity criteria allows one to determine whether or not the criteria were violated. Only a few runs of the model, using successive approximations, are needed to find the capacity of an intersection operating under a given set of circumstances. Examples of this technique are given in Chapter 3, and easily-determined, quantitative indicators for intersection levels of service are suggested.

Similarly, the geometric and traffic conditions which warrant a particular type of traffic control at an intersection can be evaluated by simulation. Intersection traffic control can range from the basic rules-of-the-road, to signs, and even to sophisticated signal schemes. Various criteria can be selected to define the quality of traffic flow through an intersection, and if a proposed scheme satisfies these criteria the geometric arrangement and controls can be said to be warranted. Chapter 4 describes how the TEXAS Model was used to study the cost effectiveness of (1) the minimum vehicular volume warrant for signals, (2) the interruption of continuous traffic warrant for signals as stated in the Manual on Uniform Traffic Control Devices, 1971 (Ref 4), and (3) the actuated signal warrant that is presented in the Texas Manual on Uniform Traffic Control Devices, 1973 (Ref 5). A variety of intersection lane arrangements, types of control, and traffic patterns were simulated in over 600 runs of the model. Conclusions are drawn concerning these existing warrants, and a tolerable delay warrant is proposed for consideration when two-way stop control is to be replaced with signalization.

CHAPTER 2. THE TEXAS MODEL FOR INTERSECTION TRAFFIC

A model for simulating intersection traffic, the TEXAS (Traffic EXperimental and Analytical Simulation) Model, has been developed at the Center for Highway Research at The University of Texas at Austin, as part of Research Study No. 3-18-72-184, under the Cooperative Research Program with the State Department of Highways and Public Transportation and the Federal Highway Administration (see Refs 1-3). This computer model accomplishes a microscopic, step-through simulation of traffic flow at a single intersection. It is a deterministic model for the most part, in that none of the response decisions is made on a probability basis. Rather, precise criteria for a particular action are established, and when these criteria are met, a programmed action is carried out. Traffic input to the model is generated, however, on a stochastic basis from descriptive information provided by the user. Since the TEXAS Model was developed especially for isolated intersections, headways in the entering traffic stream are considered to be random; therefore, headways are generated as random variates of a user-selected probability distribution function.

Structure of the Model

The TEXAS Model is a package which consists of three main computer programs. These are

(1) the geometry processor, GEOPRO;
(2) the driver-vehicle processor, DVPRO; and
(3) the simulation processor, SIMPRO.

Figure 1 shows the flow relationship among these programs.

The modular form of programming that was used provides for computational efficiency by virtue of the fact that all data which require only one computation are processed by either the geometry processor or the driver-vehicle processor and the results are stored for subsequent use. The simulation processor then performs repetitious computations related to the behavior of each vehicle.

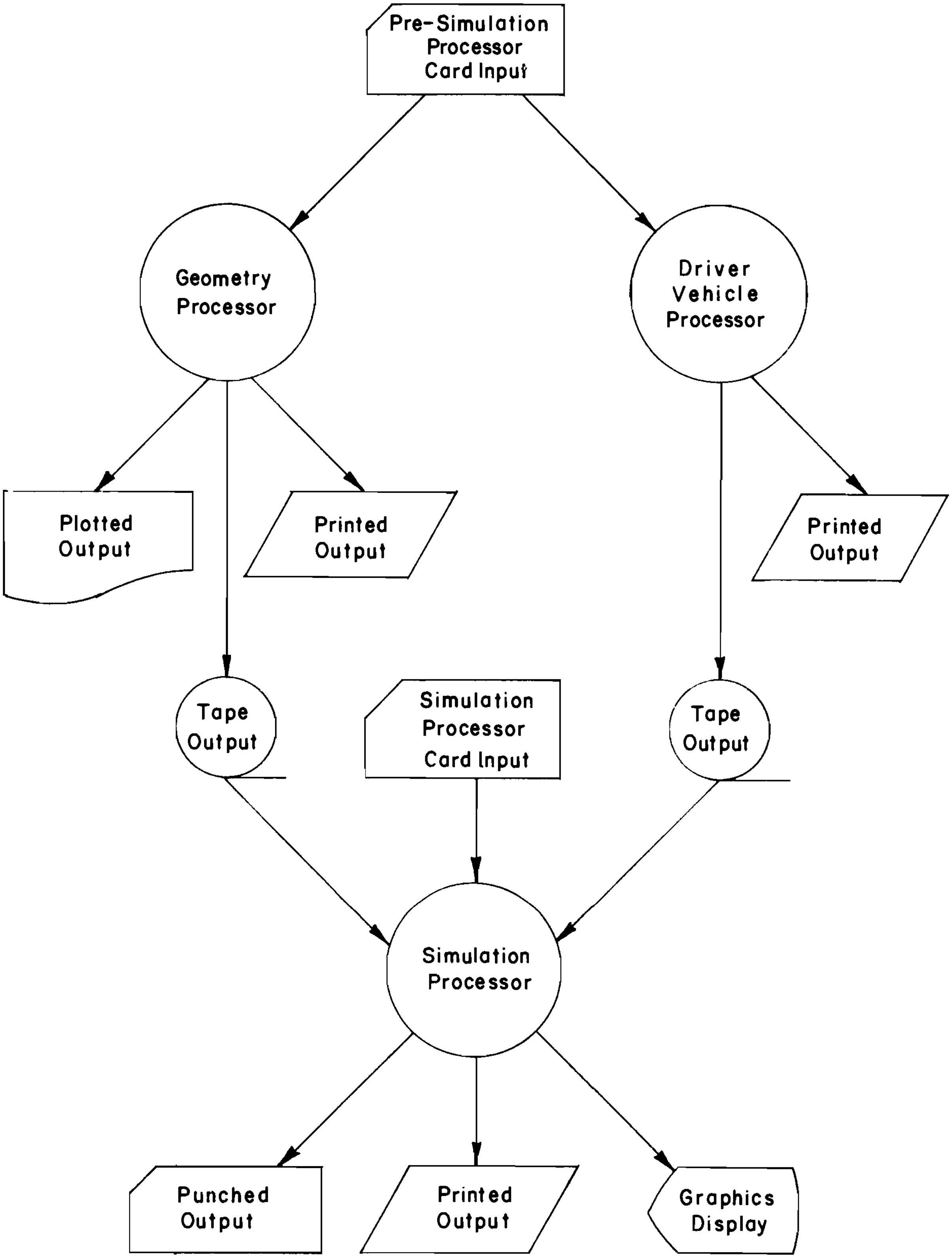


Fig 1. Flow relationship among the programs in the TEXAS Model.

The geometry processor, GEOPRO, accepts data concerning the physical configuration of the intersection such as details of the approaches, lanes, curb returns, and sight distance restrictions. Input information is coded by the user in conventional Cartesian coordinates. The processor calculates the vehicle paths on the approaches and within the intersection, the points of conflict between intersection paths, and the minimum available sight distance between approaches. GEOPRO uses straight line segments and arcs of circles to describe paths that vehicles will follow in the intersection, and safe side friction factors are used for computing the maximum speed at which a vehicle may negotiate these paths. The minimum available sight distance between inbound approaches is calculated for each 25-foot increment along the approach. Computed information is written onto a tape for later use in the simulation. A plot of the plan view of the intersection may be requested if needed.

The driver-vehicle processor, DVPRO, takes user-supplied information about the characteristics of up to 5 driver and 15 vehicle classes, generates the required descriptive data for each individual driver-vehicle unit and orders these units sequentially by queue-in time. The time headways of vehicles which arrive on each inbound approach are calculated as random variates of one of the following distributions: (1) Uniform, (2) Log Normal, (3) Negative Exponential, (4) Shifted Negative Exponential, (5) Gamma, (6) Erlang, or (7) Constant. The user chooses an appropriate distribution for each inbound approach, specifies a traffic volume for that approach, and defines an additional parameter, which indicates the expected variability in headways. An auxiliary data processor, DISFIT, is contained in the simulation package to aid the user in determining which mathematical distribution best matches any empirical headway data that might be available. In DISFIT, a value for Chi-Squared is calculated as a goodness of fit indicator for each distribution that is fitted, and the maximum cumulative difference is found for a Kolmogorov-Smirnov one-sample test. Histograms of the input headway data and of each distribution that has been fitted are also plotted to assist the user in selecting an appropriate mathematical description of the traffic pattern under investigation. Each driver-vehicle unit is assigned a lane, a turning movement, a driver class, and a vehicle class according to defined percentages using a discrete empirical distribution. Arriving vehicles are required to maintain a specified minimum safe headway, and speeds are assigned using a discrete normal distribution with a specified mean and a standard deviation calculated from the mean and the 85 percentile speed. All the computer characteristics about each driver-vehicle unit such as its arrival time, vehicle class, driver class, arrival speed, inbound approach, inbound lane, and outbound destination are written on tape for use later by the simulation processor.

The simulation processor, SIMPRO, accepts output from the geometry processor, from the driver-vehicle processor, and by direct card input. The card input specifies (a) the start-up and simulation time, (b) the time-step increment for simulation, (c) speed for "delay below XX miles per hour," (d) the maximum clear distance for being in a queue, (e) lambda, mu, and alpha values for use in the generalized car-following equations, (f) the type of intersection control, (g) the desired summary statistics, (h) time for lead and lag zones for intersection conflict checking, and (i) lane control for each lane. Many of these values are supplied automatically by the program, but the user may choose values of special interest. If the intersection is signalized, signal indication information for each lane consists of card input which models the cam stack found in most signal controllers plus the timing scheme for displaying each interval. If the intersection operates under an actuated controller, additional information about detector type and location is required.

SIMPRO uses a specified, discrete time increment, usually in the range of one-half second to one second, as the fixed time basis for scanning the intersection and updating each driver-vehicle unit. It has three types of links on which to simulate driver-vehicle units: (1) inbound lanes, where there is some form of control which regulates entry into the intersection; (2) intersection paths; and (3) outbound lanes, where there is no control at the far end. The sequential flow of the program processes driver-vehicle units on the outbound lanes, then on intersection paths, and next on inbound lanes; then new driver-vehicle units are added to the system, and finally signal status is processed. Driver-vehicle units, which are first on their link and have the right to continue to the next link, look ahead and react to the last driver-vehicle unit in the next link; thus, continuity between links is provided.

Flow through the system is assumed to attain a steady state condition after a specified start-up time. During start-up time, all movements are simulated but no performance statistics are gathered. After that, all traffic and control activities are simulated and statistics are accumulated as each vehicle logs out of the system at the end of the outbound lane. Summary statistics are reported in a tabular form at the end of the specified simulation time.

Output from the Model

Upon request, a large variety of information concerning the results of simulation can be printed, punched on cards, or shown on a graphics display screen. Summary statistics may be presented according to each inbound approach, according to selected turning movements, and for the intersection as a whole. The following statistics are included in the output:

(1) number of vehicle-seconds of delay;
(2) number and percent of driver-vehicle units delayed;
(3) average delay for delayed units;
(4) overall average delay for all units;
(5) number and percent of driver-vehicle units required to stop;
(6) total and average vehicle-miles of travel;
(7) total and average travel time;
(8) equivalent hourly volume of traffic;
(9) average desired speed;
(10) time and space mean speed;
(11) average maximum uniform acceleration and deceleration used;
(12) average and maximum length of queue on each inbound lane;
(13) average ratio of entry speed to desired speed;
(14) delay resulting from slowing below XX (specified value) miles per hour; and
(15) percent of vehicles required to slow below XX miles per hour.

Some of the statistics that are computed during simulation are difficult, or nearly impossible, to obtain from field observations of traffic. The fact that these values, along with all conventional descriptors of traffic behavior, are incorporated in the output from the TEXAS Model makes application of this simulation package a particularly powerful tool for analyzing intersection performance.

As will be pointed out later in this report, the items of output that are of significance in determining intersection capacity and level of service are

(1) total intersection volume, (2) percent of vehicles required to stop, (3) percent of vehicles required to slow below 10 miles per hour, (4) average queue delay, and (5) average stopped delay. In evaluating warrants for traffic control at intersections, additional summary statistics relating to (1) approach volume, (2) total queue delay, and (3) total stopped delay were found to be valuable indicators of performance.

Computer Requirements

FORTRAN IV language has been used to implement the TEXAS Model on both Control Data Corporation (CDC6600) and International Business Machines (IBM370-155) computers.

The geometry processor, GEOPRO, requires 29,760 words (72,100 octal) of storage on CDC computers and 176,000 bytes of storage on IBM computers. Geometry computations for an average intersection (4 inbound and 4 outbound approaches, 2 lanes per approach, 4 sight distance restriction coordinates, and PRIMARY intersection paths) take 6.3 central processor seconds on CDC computers and 9.2 central processor seconds (0.153 minutes) on IBM computers.

The driver-vehicle processor, DVPRO, requires 17,216 words (41,500 octal) of storage on CDC computers and 102,000 bytes of storage on IBM computers. The driver-vehicle processor requires approximately 3 seconds of computer time on CDC computers and 4 seconds (0.067 minutes) on IBM computers to generate a moderate flow of driver-vehicle units for an average intersection of 4 inbound and 4 outbound approaches, 2 lanes per approach.

The simulation processor, SIMPRO, uses 32,704 words (77,700 octal) of storage on CDC computers and 210,000 bytes of storage on IBM computers. The computer time requirements for SIMPRO are difficult to reduce to a single value. As an indication of the efficiency of the model, a simulation time to computer time ratio for CDC computers has been calculated for each run of SIMPRO. This ratio varies with the type of intersection control, the lane lengths, the time increment, and the total number of driver-vehicle units processed. For signalized intersections, 600-foot (182.88-meter) lanes, and a time increment of one second, the lower limit of efficiency (worst case) is in the general range from 30 at a total equivalent hourly volume of 1,000 vehicles per hour to 8 at a volume of 2,000 vehicles per hour. The upper limit of efficiency (best case) is 45 and 15, respectively, for the same volumes. For non-signalized intersections, 600-foot (182.88-meter) lanes, and a time increment of 0.5 seconds, the lower limit of efficiency (worst case) is in the general range from 40 at a volume of 750 vehicles per hour to 8 at a volume of 1,250 vehicles per hour. These efficiencies may be different for other computer systems.

CHAPTER 3. INTERSECTION CAPACITY ANALYSIS USING THE TEXAS MODEL

Traffic engineers and transportation planners are faced with the task of designing road facilities and traffic control schemes which provide for safe and efficient movement of people and freight. Intersections are critical components of this system and a single intersection may be responsible for limiting the capacity of an entire road network. An accurate and convenient method for determining the capacity of an intersection is thus needed.

The methods currently available for analyzing the capacity of intersections are mostly empirical, probabilistic, or based on sample observations. In the empirical methods, historical experience and analysis are usually reduced to charts, tables, and adjustment factors. Probabilistic methods utilize statistical distributions to represent traffic characteristics such as headway, spacing, and speed. Expected interactions are computed and shown as graphs or formulae for capacity. Observation methods involve field sampling and forecasting. Time-lapse photography has sometimes been used to record traffic movements at representative intersections; then data from the pictures have been analyzed and reduced to formulae for capacity.

Since these methods are generally macroscopic and are intended to be applicable over a wide range of situations, they usually do not consider individual driver-vehicle movements. Most techniques for capacity analysis are concerned with signalized intersections, and a method that can readily be used to determine the capacity of unsignalized intersections is not currently available. There is a need for a practical method of estimating the capacity of intersections operating under any conventional form of control, or with no control, whereby the behavior of each vehicle in the traffic system can be accounted for.

Capacity and Level of Service Concept

Before 1965, three levels of intersection capacity were generally recognized (Ref 6):

(1) basic capacity - the maximum number of vehicles that can be accommodated under the most nearly ideal traffic conditions which can possibly be attained;

(2) possible capacity - the maximum number of vehicles that can be accommodated under prevailing traffic conditions with a continual backlog of waiting vehicles; and

(3) practical capacity - the maximum number of vehicles that can be accommodated under prevailing traffic conditions with no vehicle incurring undue delay.

Having identified only two categories for prevailing traffic conditions was thought to be inadequate in practice, and it was felt that it would be more definitive to describe intersection traffic flow in terms of a range of values. Capacity is now defined (Ref 7) as the maximum traffic volume accommodated under a given set of conditions. Practical capacity has been replaced by several service volumes representing any of several specific traffic volumes related to a group of desirable operating conditions collectively termed "level of service."

Level of service is the qualitative measure of the effect of a number of factors, which include speed and travel time, traffic interruptions, freedom to maneuver, safety, driving comfort and convenience, and operating costs. Each level of service has associated with it a "service volume" which is the maximum volume that can be accommodated while providing the specified level of service. The service volume at level of service "E" is the maximum volume that can be accommodated by the intersection under prevailing conditions and is thus the capacity of the intersection. This definition corresponds to the previously defined possible capacity. Six levels of service, identified alphabetically from "A" to "F," have been selected for application in defining the quality of intersection operating conditions.

Level of Service	Flow Condition	Description
A	Free flow	No waiting vehicles
B	Stable flow	Restricted within platoons
C	Stable flow	Back-ups develop behind turning vehicles
D	Approaching unstable flow	Substantial delays
E	Unstable flow	Capacity
F	Forced flow	No movement

One measure of intersection level of service is user satisfaction. A facility can be said to provide a high level of service if the user is pleased to drive through the intersection. This means that each driver may choose the speed that he wants and pass through the intersection without unreasonable hindrance.

In the case of uninterrupted flow on sections of roadway between intersections, speed is generally used as a measure of level of service, and speed-volume curves are used to describe the level of service under which the section operates. However, at intersections, the inherent stop-go nature of traffic makes such a relationship difficult to interpret. Speed is, therefore, not considered to be a good indicator of performance in this situation, and a different indicator of level of service is desired.

The level of service at intersections depends on the manner in which the traffic flows through the intersection. At signalized intersections, load factor is widely accepted as a performance indicator for level of service (Ref 7). Load factor is defined as the ratio of the number of fully utilized green phases in a series of signal cycles to the total number of green phases in the same series. Load factor is easy to measure in the field, since all that is required is a count of the green phases during which vehicles are continually present and the total number of green phases displayed in the selected time period. Load factor is the ratio of these two numbers. Numerical limits of load factor for various levels of service are given as

Level of Service	Traffic Flow Description	Load Factor
A	Free flow	0.0
B	Stable flow	<0.1
C	Stable flow	<0.3
D	Approaching unstable flow	<0.7
E	Unstable flow	<1.0
F	Forced flow	---

Even though load factor is used extensively to identify intersection levels of service, it is not an ideal descriptor. Its applicability is limited to signalized intersections, and the break points between the various levels of service have no strong rational basis. A better, and more widely applicable, means for expressing the quality of intersection performance as perceived by the user in quantitative terms is desired.

Indicators of Level of Service

Indicators that can be used at intersections with all forms of traffic control are needed to identify the level of service that is provided. The selection of appropriate indicators can be considered from two points of view. The designer prefers indicators that can be measured easily in quantitative terms, while the user perhaps comprehends more subjective measures of his satisfaction. Indicators which relate to both these points of view should be selected for evaluating the performance of intersections. The selected indicators must be easy to measure quantitatively, and the user must be able to relate them to his personal satisfaction. If simulation is to be used in capacity analysis, any indicator of level of service should be readily attainable from the simulation model.

The following indicators appear to be appropriate measures of level of service at intersections in that they incorporate all the desired features stated above.

(1) Queue delay: Queue delay is the delay experienced when a vehicle is in a queue. A vehicle can be said to be in a queue if all the following conditions are satisfied:

(a) The vehicle is at a virtual stop. A vehicle moving slower than, say, 2 mph is considered to be stopped.

(b) An object ahead, such as a stop sign, requires the vehicle to stop, or the vehicle immediately ahead is in a queue.

(c) The vehicle is less than a prescribed distance (e.g., 30 feet) from an object which requires a stop.

Once a vehicle is in a queue, it is considered to remain in the queue until it enters the intersection, even if its speed exceeds 2 mph while moving forward in the queue. Queue delay is thus measured from the time the vehicle enters the queue until the time it enters the intersection and includes time spent in moving up in the queue. Since vehicles at unsignalized intersections experience this type of delay, queue delay is an appropriate criterion that may be used to evaluate delay at unsignalized intersections. Queue delay is readily identified by the user as an index of intersection performance since the user prefers to travel through intersections under circumstances whereby minimum time is spent waiting in a queue. As average queue delay is one of the statistics compiled from simulation by the TEXAS Model, it is a readily available quantitative factor that may be used as a level of service indicator.

In field studies, queue delay can be measured (1) by enumerating the number of vehicles in the queue at fixed, periodic time intervals (point sample), (2) by the input-output method, (3) by path trace based on a sample of individual vehicles, and (4) by time-lapse photography. A special device for recording queue delay by the point sample technique on a one-second time basis is described in Ref 1.

A recent study by Sutaria and Haynes (Ref 8) utilized the opinions of 310 drivers with a wide variety of driving experience to evaluate intersection levels of service. Each participant in the study was first asked to rank the following factors according to their relative importance in defining the quality of service provided by an intersection: (1) delay, (2) number of stops, (3) traffic congestion, (4) number of trucks and buses in the traffic stream, and (5) difficulty in lane changing. Then, each driver was shown a series of photographs of a signalized intersection in Fort Worth, Texas, operating under a variety of traffic conditions, or levels of service. A majority of the drivers indicated both before and after viewing the pictures that delay was the most important factor in their subjective evaluation of intersection performance.

(2) Percent of vehicles that are required to stop: Percent of vehicles that are required to stop is easy to measure in the field simply by counting

all the vehicles that stop and the total traffic volume for a selected period of time. No special equipment is required for these measurements. It is apparent to the driver that the intersection behaves more satisfactorily if most vehicles can pass through without having to stop. This parameter is also available in the summary statistics of the TEXAS Model. Since percentage required to stop is easier to measure than average queue delay, this indicator might be preferable to intersection designers as a level of service indicator. It is applicable only at uncontrolled and yield-sign controlled intersections, however, as at stop-sign controlled intersections, all vehicles on approaches facing the stop signs are required to stop. An advantage of using this parameter is that the stage at which an uncontrolled or yield-sign controlled intersection behaves similarly to a stop-sign controlled intersection can be observed, since, at that point, a high percentage of vehicles will be required to stop.

(3) Percent of vehicles required to slow to below 10 mph: This indicator relates directly to driver satisfaction since no driver likes to slow to below 10 mph. The percentage of vehicles that have to slow below 10 mph is difficult to determine in field studies, however. This can possibly be measured in the field using time-lapse photography. The TEXAS Model computes this value from simulation and makes it available for comparing the performance of various types of unsignalized intersections. A further incentive for considering this indicator is that the 1971 version of the Manual on Uniform Traffic Control Devices (MUTCD) (Ref 4, p 34) states:

> The Yield Sign may be warranted:
>
> On a minor road at the entrance to an intersection where it is necessary to assign right-of-way to the major road, but where a stop is not necessary at all times, and where the safe approach speed on the minor road exceeds 10 miles per hour.

Relating Selected Performance Indicators to Level of Service

Since queue delay can feasibly be used as an indicator of level of service for all types of intersection control, a quantitative relationship between queue delay and level of service, similar to the one that has been recognized between load factor and level of service, is desired. Once this relationship is established, the maximum volume that can be accommodated at each level of service can be determined.

May and Pratt (Ref 9) established a relationship between average delay and load factor for signalized intersections and then linked average delay to level of service by using recognized relationships between load factor and level of service. They conducted simulation experiments to establish the relationship between level of service and load factor. For their simulation studies, May and Pratt generated arrival times for vehicles on each intersection approach by using a random headway distribution with a minimum input headway of one second. The randomly generated numbers were multiplied by 3600 and arranged in a chronological order to obtain individual arrival times for vehicles within a one-hour period. The simulated intersection was controlled by a pre-timed signal with a 60-second cycle and equal red and green phases.

The minimum headway for discharging vehicles depended on the desired specific capacity. For example, a capacity of 600 veh/hr meant that the capacity per cycle was $600/60 = 10$. For 30 seconds of green, the uniform discharge headway was $30/10 = 3$ seconds. Other discharge headways could similarly be calculated by assuming other specific capacities. A vehicle was not permitted to leave until the calculated discharge headway time had elapsed. The load factor and the average delay incurred by each vehicle were noted, and a graph (Fig 4, Ref 9, p 44) was drawn. From this graph and Table 6.3 of the Highway Capacity Manual (Ref 7, p 131), a table relating average delay to level of service (Table I, Ref 9, p 47) was constructed. May and Pratt then utilized the relationship between load factor and level of service developed in the Highway Capacity Manual and obtained a new relationship in which level of service was based on approximately equivalent average individual delay. This relationship is presented in Table II, Ref 9, p 47.

May and Pratt's analysis demonstrated that average delay could be used as an indicator of level of service in place of load factor at signalized intersections. Capacity analysis of unsignalized intersections would be facilitated if a similar relationship between average queue delay and level of service could be developed for unsignalized control.

Operational delays for a given level of service should be consistent regardless of the type of control at the intersection. May and Pratt's analysis defines reasonable and orderly relationships between average delay and level of service at signalized intersections. These same values can be used to describe levels of service at unsignalized intersections.

After making a large number of runs of the TEXAS Model for a 4-lane by 4-lane all-way stop-sign-controlled intersection for a wide range of traffic demand, a graph of total intersection volume against average queue delay (Fig 2) was drawn. A quite similar relationship was found for a 2-lane by 2-lane all-way stop-sign-controlled intersection. Horizontal lines representing average delay for the various levels of service shown in Table II, Ref 9, p 47 (see also Col 2, Table 1), were superimposed on the graph. Column 3 in Table 1 shows the volume of traffic accommodated at these levels of service as read from Fig 2. For comparison, average delay as suggested by Sutaria and Haynes (Ref 8) is shown in Col 4 of Table 1. Table 1, then, shows the interrelationships among level of service, average delay, and volume accommodated. The volume at each level of service can be judged to be reasonable and can be expected to result in the general flow conditions described in the Highway Capacity Manual (Ref 7).

The Manual on Uniform Traffic Control Devices (Ref 4, p 33) states that one of the conditions which might warrant a stop sign is an average delay of at least 30 seconds per vehicle during the maximum hour. Since an average delay of 30 seconds is the upper boundary suggested for level of service B (see Table 1), this adds validity to the choice of 30 seconds as the boundary between levels of service B and C at which intersections normally operate. In Ref 10 this is further discussed, and a relationship was established between volume warrants and 20, 30, and 35 seconds of average delay (Table 5.2, Ref 10, p 84). This would correspond to levels B, B/C, and C, according to Table 1.

Average queue delay can be used as a measure of level of service for all intersections. However, for uncontrolled and yield-controlled intersections, a more convenient indicator of level of service might be the percentage of vehicles that are required to stop, since it is easier to measure the percent stopped and these intersections operate as stop-controlled intersections if a high percentage of vehicles are required to stop. For yield-controlled intersections, another indicator is the percentage required to slow to below 10 mph, since a commonly accepted warrant for that control is that it may be used if the approach speed exceeds 10 mph.

These two performance indicators, (1) percentage of vehicles required to stop and (2) percentage of vehicles required to slow to below 10 mph, may also be related to level of service. To establish these relationships, the TEXAS

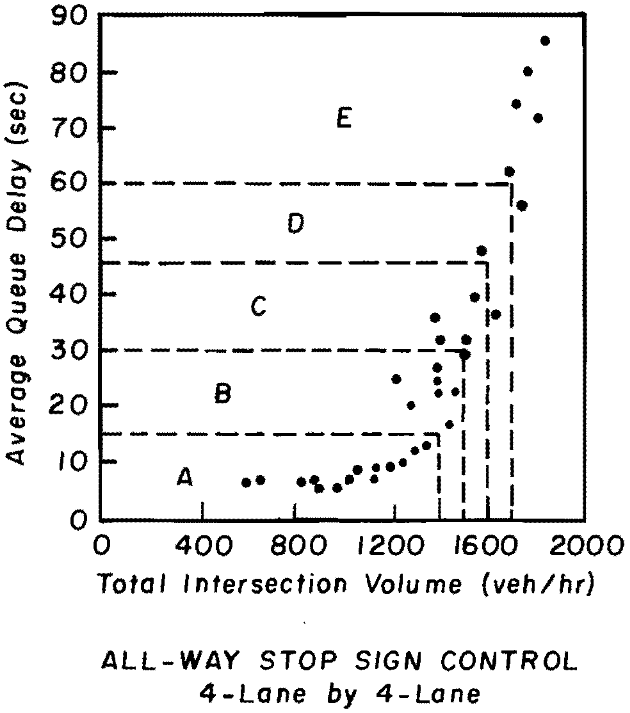


Fig 3. Service volumes at various levels of service as indicated by average queue delay for an all-way stop-sign controlled intersection.

TABLE 1. INTERRELATIONSHIPS AMONG LEVELS OF SERVICE, AVERAGE DELAY, AND VOLUME ACCOMMODATED AT ALL-WAY-STOP-SIGN-CONTROLLED INTERSECTIONS

Level of Service (Column 1)	Average Delay,* sec/veh (Column 2)	Average Volume,** veh/hr (Column 3)	Average Delay,*** sec/veh (Column 4)
A	≤ 15	≤ 1400	≤ 12.6
B	≤ 30	≤ 1500	≤ 30.1
C	≤ 45	≤ 1600	≤ 47.7
D	≤ 60	≤ 1700	≤ 65.2
E	> 60	> 1700	≤ 82.8

*Source: Table II on page 47 of Ref 9

**Source: Figure 2

***Source: Table 6-B, page 24, Ref 8

Model was run to examine traffic behavior at a representative yield-sign controlled intersection under a wide range of demand volume; and the average queue delay resulting from different percentages of vehicles slowing to below 10 mph and the average queue delay resulting from different percentages of vehicles required to stop were obtained. Figure 3 is a graph of percent of side-street vehicles slowing to below 10 mph against average queue delay, and Fig 4 shows percent of vehicles required to stop against average queue delay. On both these graphs, horizontal lines representing levels of service for different values of average queue delay determined earlier (see Table 1) are superimposed. From these graphs, the level of service for different percentages of side-street vehicles slowing to below 10 mph (Table 2, Col 3) and the level of service for different percentages of vehicles that were required to stop (Table 2, Col 4) can be read. Table 2 shows the relationship among level of service, average queue delay, percent slowing to below 10 mph, and percent required to stop.

Recommended Performance Indicators for Unsignalized Intersections

For stop-sign controlled intersections, average queue delay is recommended as the best indicator of level of service. Average queue delay can be measured in the field by appropriate survey techniques, it can be comprehended by the user, and it can be simulated by the TEXAS Model. Suggested relationships between average queue delay and the various levels of service are presented in Table 1.

For yield-sign controlled intersections, both the percentage of side-street vehicles that have to slow below 10 mph and those that have to stop can be considered as good indicators of level of service. The percentage of vehicles that have to slow to below 10 mph can be determined from simulation or it can be measured in the field using time-lapse photography; it can also be understood by the user. Too, this parameter has been recognized as the basis of a warrant for yield-sign control of intersections. Suggested relationships between percent of vehicles slowing to below 10 mph and various levels of service are presented in Table 2. The percentage of side-street vehicles that have to stop can be measured easily in the field, it is easily understood by the user, and it can be simulated by the TEXAS Model. Suggested relationships between percent of vehicles that have to stop and levels of service are also presented in Table 2.

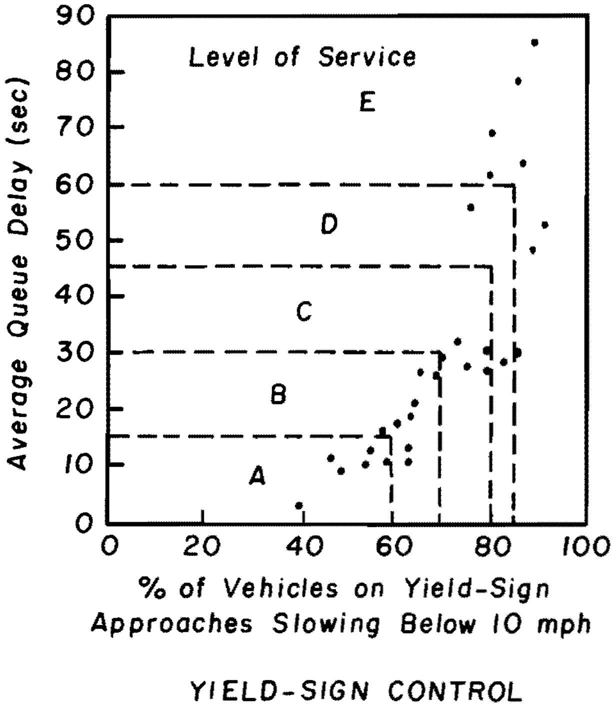


Fig 2. Levels of service at yield-sign-controlled intersections as indicated by average queue delay and percent of vehicles on signed approaches slowing below 10 mph.

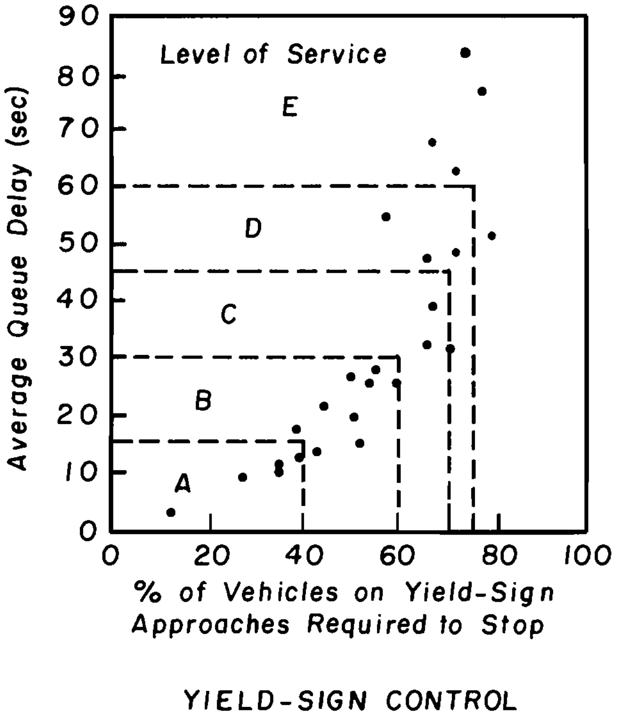


Fig 4. Levels of service at yield-sign-controlled intersections as indicated by average queue delay and percent of vehicles on signed approaches required to stop.

TABLE 2. RELATIONSHIP AMONG LEVEL OF SERVICE, AVERAGE QUEUE DELAY, PERCENT SLOWING TO BELOW 10 MPH, AND PERCENT REQUIRED TO STOP

Level of Service (Column 1)	Average Queue Delay (Column 2)	Percent of Vehicles Slowing to Below 10 mph (Column 3)	Percent of Vehicles Required to Stop (Column 4)
A	< 15 secs	< 60 percent	< 40 percent
B	< 30 secs	< 70 percent	< 60 percent
C	< 45 secs	< 80 percent	< 70 percent
D	< 60 secs	< 85 percent	< 75 percent
E	> 60 secs	> 85 percent	> 75 percent

For uncontrolled intersections, percent of vehicles that are required to stop is considered to be the most appropriate indicator of level of service, since it can be measured very easily in field studies. The relationship between percent of vehicles that are required to stop and level of service as suggested in Table 2 can be used in evaluating uncontrolled intersections.

Table 3 is a summary tabulation of recommended performance indicators for various levels of service at each type of unsignalized intersection. Suggested values for signalized intersections (Ref 9) are also included in this table for convenience.

Capacity Analysis Procedure Using the TEXAS Model

An intersection is characterized by its geometry, type of control, volume accommodated, and level of service provided. Generally, if any three of these factors are known, the fourth can be determined. To use the TEXAS Model, all data regarding geometrics, traffic characteristics, and volume conditions that are known are collected and input to the geometry and driver-vehicle processors and to the simulation processor. The summary statistics that are reported from the run are analyzed to provide the required information. Four cases are now described in which the TEXAS Model can be used to evaluate the performance of an unsignalized intersection.

Case I

Known: Lane configuration, type of control, and volume accommodated

Desired: Level of service

Method: The TEXAS Model is run with the known geometry and control at the accommodated volume. The value of an appropriate performance indicator is determined from the summary statistics, and then from Table 3 the level of service is determined.

Case II

Known: Lane configuration, type of control, and level of service

Desired: Service volume that can be accommodated

Method: An estimate of the volume is made. Then the TEXAS Model is run with the geometry, type of control, and estimated volume. The value of the appropriate performance indicator is determined from the summary statistics. The level of service that is provided is determined from Table 3. If this is

TABLE 3. RECOMMENDED INDICATORS OF INTERSECTION LEVELS OF SERVICE

Type of Intersection Control	Uncontrolled	Yield-Sign Control		Two-Way Stop Control	All-Way Stop Control	Signal Control
Recommended Performance Indicator / Level of Service	Percent of all Vehicles That Must Stop	Percent of Vehicles on Sign-Controlled Approaches That Must Slow Below 10mph	Percent of Vehicles on Sign-Controlled Approaches That Must Stop	Average Queue Delay* to Vehicles on Sign-Controlled Approaches	Average Queue Delay* to Vehicles on All Approaches	Average Stopped-Delay** to Vehicles on All Approaches
A	< 40%	< 60%	< 40%	< 15 sec	< 15 sec	< 15 sec
B	< 60%	< 70%	< 60%	< 30 sec	< 30 sec	< 30 sec
C	< 70%	< 80%	< 70%	< 45 sec	< 45 sec	< 45 sec
D	< 75%	< 85%	< 75%	< 60 sec	< 60 sec	< 60 sec
E	> 75%	> 85%	> 75%	> 60 sec	> 60 sec	> 60 sec

*Queue delay is the time spent by a vehicle while at a virtual stop in a queue of vehicles on an intersection approach. It is measured from the time the vehicle joins the queue until the vehicle enters the intersection, and thus includes move-up time.

**Stopped delay is the time spent by a vehicle while actually stopped on an intersection approach; it does not include move-up time.

not the level desired, a fresh estimate of the volume is made and the process is repeated until the intersection can be expected to operate at the desired level of service. Usually two or three runs will be sufficient to estimate the service volume.

Case III

Known: Lane configuration and type of intersection control

Desired: The level of service provided for different volumes, or the maximum volume that can be accommodated at each level of service

Method: The TEXAS Model is run for the known geometry and control at a range of volumes that could be expected to cover all the levels of service. From summary statistics, a graph of volume against the specific indicator can be drawn, and a table linking volume to level of service, using Table 3 as a guide, can be constructed. This table is then used to determine the desired information.

Case IV

Known: Volume to be accommodated and level of service to be provided

Desired: Optimum design (lane configuration and control)

Method: A lane configuration and a control scheme are chosen. Then the TEXAS Model is run with the desired volume, and from summary statistics and Table 3 the level of service that will be provided is determined. If this level of service is not satisfactory, a fresh choice of geometry and control is made, and the process is repeated until the desired level of service is attained at that volume. Two or three runs should be sufficient to design the intersection.

A working example using a step-by-step procedure is now described to illustrate these four cases.

Example

For Case I, the level of service at which a 2-lane by 2-lane uncontrolled intersection accommodating 1600 veh/hr will operated will be determined. For Case II, the maximum volume that can be accommodated by a 2-lane by 2-lane uncontrolled intersection operating at a level of service B will be determined. For Case III, the levels of service at different volumes and the maximum volume that can be accommodated at each level of service by a 2-lane by 2-lane uncontrolled intersection will be analyzed using a graph and a table that will be constructed. For Case IV, the optimum lane configuration and type of intersection control to accommodate 1600 veh/hr while maintaining a level of service A will be determined.

Geometry of the Intersection. The intersection is assumed to be a right-angled intersection with four approaches and four exits. For the first three cases, each leg of the intersection has one lane in each direction. The number of lanes for the fourth case will be determined based on the volume to be accommodated and the level of service to be maintained. Each lane is 10 feet wide. The influence of the intersection extends 800 feet in advance of the intersection on each inbound lane and 400 feet beyond the intersection on each outbound lane. The speed limit is 35 mph on all approaches. There are no sight distance restrictions. A plot of the intersection used for the example in Cases I, II, and III is shown in Fig 5.

Traffic Data

(1) The distribution of traffic on each approach was found to be

Approach	Direction	Percentage of Total Volume
1	Northbound	15
2	Westbound	25
3	Southbound	25
4	Eastbound	35

(2) On two inbound lanes, 45 percent of the vehicles were assumed to be in the median lane, and 55 percent of the vehicles were in the curb lane (Case IV).

(3) In every case, 15 percent of the vehicles turned right, 10 percent of the vehicles turned left, and 75 percent of the vehicles went straight through.

(4) On the minor (North-South) approaches, the mean speed was 25 mph, and the 85 percentile speed was 30 mph. On the major (East-West) approaches, the mean speed was 30 mph, and the 85 percentile speed was 35 mph.

(5) The arrival headway pattern was described by the negative exponential distribution.

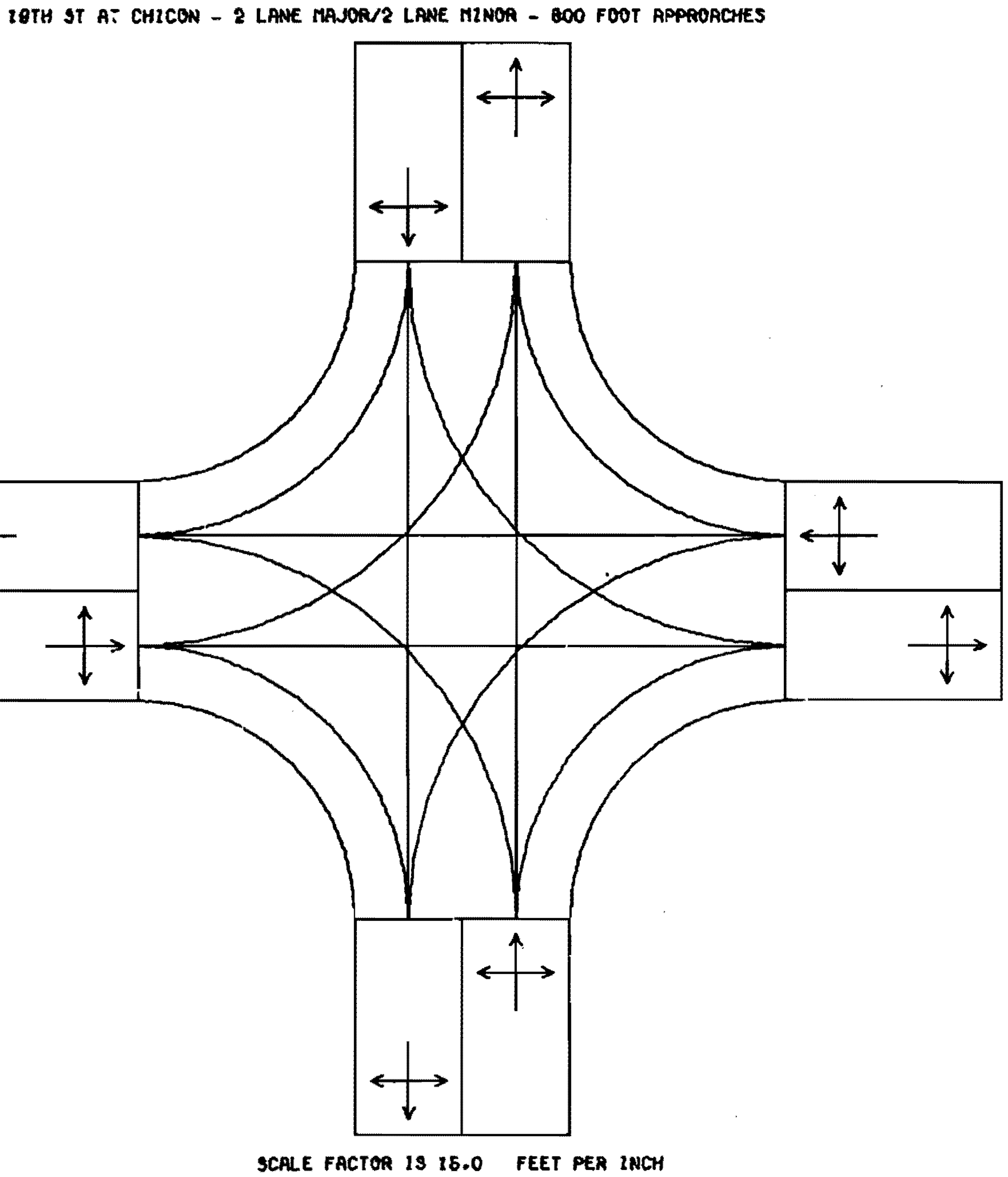


Fig 5. Intersection used for example Cases I, II, and III.

(6) The program-supplied values for the percentage of vehicles in each vehicle class and the percentage of drivers in each driver class were used. These values are presented in Table 4.

Simulation. Starting with no vehicles in the system, generated driver-vehicle units were positioned at the start of the approach according to the calculated arrival time. Then, depending on the desired speed, destination, traffic condition, and relative position in the intersection area, each unit responded logically to its surroundings. The system was scanned and updated at fixed intervals of one-half second. Each unit was processed through the approach. Flow through the system was assumed to attain a steady-state condition in two minutes of real time. Until then, all the movements were simulated, but no statistics were gathered. After that, all movements were simulated and statistics were accumulated as each vehicle logged out of the system at the end of the exit. The duration of simulation for this example was 10 minutes of real time. Figure 6 shows the summary statistics for the intersection used in this example. The intersection was uncontrolled, in Cases I, II, and III; therefore, the total intersection volume and the percent of vehicles that were required to stop were used for capacity analysis.

Analysis

The four cases described earlier are evaluated here.

Case I. For a 2-lane by 2-lane uncontrolled intersection that accommodates a volume of 1600 veh/hr, Fig 6 shows that the percent of vehicles required to stop is 79.5. From Table 3, the level of service provided is E.

Case II. For a 2-lane by 2-lane uncontrolled intersection that is to operate at a level of service B, the first estimate of volume was 1300 veh/hr. The percent delayed in this case after running the model in the manner described above was 51.7. The level of service provided is B, but this is not the maximum volume that can be accommodated. The model was next run with a volume of 1500 veh/hr. The percentage stopping now was 68.4. The level of service that is provided in this case is C. Next the model was run with a volume of 1400 veh/hr. The percentage of vehicles that is now required to stop is 59.3. This percentage is very close to the upper boundary of level of service B. Thus, it can be stated that the capacity of a 2-lane by 2-lane uncontrolled intersection operating under a level of service B is 1400 veh/hr.

TABLE 4. PROGRAM-SUPPLIED VALUES FOR DRIVER-VEHICLE CHARACTERISTICS

	Vehicle Class and Type									
	1 Small Car	2 Medium Car	3 Large Car	4 Vans, Mini-bus	5 Single-unit	6 Semi-trailer	7 Full-trailer	8 Recreational	9 Bus	10 Sports Car
Length	15	17	19	25	30	50	55	25	35	14
Operating Characteristic Factor	100	110	110	100	85	80	75	90	85	115
Maximum Deceleration	16	16	16	16	12	12	12	12	12	16
Maximum Acceleration	8	9	11	8	8	7	6	6	5	14
Maximum Velocity	150	192	200	150	160	160	150	150	125	205
Minimum Turning Radius	20	22	24	28	42	40	45	28	28	20
Percentage Aggressive Drivers	30	35	20	25	40	50	50	20	25	50
Percentage Average Drivers	40	35	40	50	30	40	40	30	50	40
Percentage Slow Drivers	30	30	40	25	30	10	10	50	25	10
Percentage in Traffic Stream	20	32	30	15	.5	.2	.1	.2	.5	1.5

Driver Class and Type	1 Aggressive	2 Average	3 Slow
Driver Characteristic	110	100	85
Perception Reaction Time	0.5	1.0	1.5

```
TEXAS TRAFFIC AND INTERSECTION SIMULATION PACKAGE - SIMULATION PROCESSOR

 *****      NSIM5BU - HIGHLAND HILLS - DRIVE AT CIRCLE * UNCONTROLLED

SUMMARY STATISTICS FOR ALL APPROACHES


TOTAL DELAY (VEHICLE-SECONDS) -------------------- =   10003.3
NUMBER OF VEHICLES INCURRING TOTAL DELAY --------- =     254
PERCENT OF VEHICLES INCURRING TOTAL DELAY -------- =     100.0
AVERAGE TOTAL DELAY (SECONDS) -------------------- =      39.4
AVERAGE TOTAL DELAY/AVERAGE TRAVEL TIME ---------- =      55.5 PERCENT

QUEUE DELAY (VEHICLE-SECONDS) -------------------- =    7441.0
NUMBER OF VEHICLES INCURRING QUEUE DELAY --------- =     202
PERCENT OF VEHICLES INCURRING QUEUE DELAY -------- =      79.5
AVERAGE QUEUE DELAY (SECONDS) -------------------- =      36.8
AVERAGE QUEUE DELAY/AVERAGE TRAVEL TIME ---------- =      51.9 PERCENT

STOPPED DELAY (VEHICLE-SECONDS) ------------------ =    1674.0
NUMBER OF VEHICLES INCURRING STOPPED DELAY ------- =     202
PERCENT OF VEHICLES INCURRING STOPPED DELAY ------ =      79.5
AVERAGE STOPPED DELAY (SECONDS) ------------------ =       8.3
AVERAGE STOPPED DELAY/AVERAGE TRAVEL TIME -------- =      11.7 PERCENT

DELAY BELOW 10.0 MPH (VEHICLE-SECONDS) ----------- =    9921.0
NUMBER OF VEHICLES INCURRING DELAY BELOW 10.0 MPH - =     236
PERCENT OF VEHICLES INCURRING DELAY BELOW 10.0 MPH  =      92.9
AVERAGE DELAY BELOW 10.0 MPH (SECONDS) ----------- =      42.0
AVERAGE DELAY BELOW 10.0 MPH/AVERAGE TRAVEL TIME -- =      59.3 PERCENT

VEHICLE-MILES OF TRAVEL -------------------------- =      61.487
AVERAGE VEHICLE-MILES OF TRAVEL ------------------ =        .242
TRAVEL TIME (VEHICLE-SECONDS) ---------------------=   18017.1
AVERAGE TRAVEL TIME (SECONDS) -------------------- =      70.9
NUMBER OF VEHICLES PROCESSED --------------------- =     254
VOLUME PROCESSED (VEHICLES/HOUR) ----------------- =    1524.0
TIME MEAN SPEED (MPH) = MEAN OF ALL VEHICLE SPEEDS  =      14.9
SPACE MEAN SPEED (MPH) = TOT DIST / TOT TRAVEL TIME =      12.3
AVERAGE DESIRED SPEED (MPH) ---------------------- =      28.3
AVERAGE MAXIMUM ACCELERATION (FT/SEC/SEC) -------- =       4.5
AVERAGE MAXIMUM DECELERATION (FT/SEC/SEC) -------- =       4.3

OVERALL AVERAGE TOTAL DELAY (SECONDS) ------------ =      39.4
OVERALL AVERAGE QUEUE DELAY (SECONDS) ------------ =      29.3
OVERALL AVERAGE STOPPED DELAY (SECONDS) ---------- =       6.6
OVERALL AVERAGE DELAY BELOW 10.0 MPH (SECONDS) ---- =      39.1

NUMBER OF VEHICLES ELIMINATED (LANE FULL) -------- =       7

AVERAGE OF LOGIN SPEED/DESIRED SPEED (PERCENT) ---- =      87.7
```

Fig 6. Example of summary statistics.

Figure 7 is a graph of total intersection volume against percent of vehicles that are required to stop for these three runs.

Case III. An analysis of a 2-lane by 2-lane uncontrolled intersection was conducted by running the TEXAS Model with a wide range of volumes. From the summary statistics reported, a graph of total intersection volume against the percentage of vehicles that are required to stop was drawn (Fig 8). Horizontal lines representing levels of service, obtained from Table 3, were superimposed, and a table relating level of service to total intersection volume was constructed (Table 5). Table 5 can be used to find the level of service provided at any volume and the maximum volume that can be accommodated at each level of service for a 2-lane by 2-lane uncontrolled intersection. Similar graphs and tables can be constructed for other traffic controls and lane arrangements.

Case IV. To design the intersection so that 1600 veh/hr can be accommodated while a level of service A is maintained, different lane arrangements and traffic control schemes were tried. The TEXAS Model was run with these geometrics and controls with a volume of 1600 veh/hr until the desired level of service was attained. An efficient and economical way would be to try the arrangement most likely. For a first trial, a 2-lane by 2-lane stop-sign controlled intersection was tried. The level of service that was provided was D, so a 4-lane by 4-lane two-way stop-sign controlled intersection was tried. The level of service that was now provided was A. Other combinations were tried, but no other lane arrangement and traffic control scheme gave a level of service of A. Table 6 is a matrix of lane arrangements and control schemes that were run showing the level of service that will be provided under each scheme. This table can be used in two ways. It can be used to determine the level of service of an existing or proposed intersection, or it can be used to design an intersection to provide any desired level of service. This table is to be used when the total intersection volume is 1600 veh/hr. Similar tables can be constructed for different intersection volumes.

Summary

A method for determining the capacity and level of service of unsignalized intersections using the TEXAS Model for Intersection Traffic has been described in this chapter. Hitherto, the manner of determining capacity has

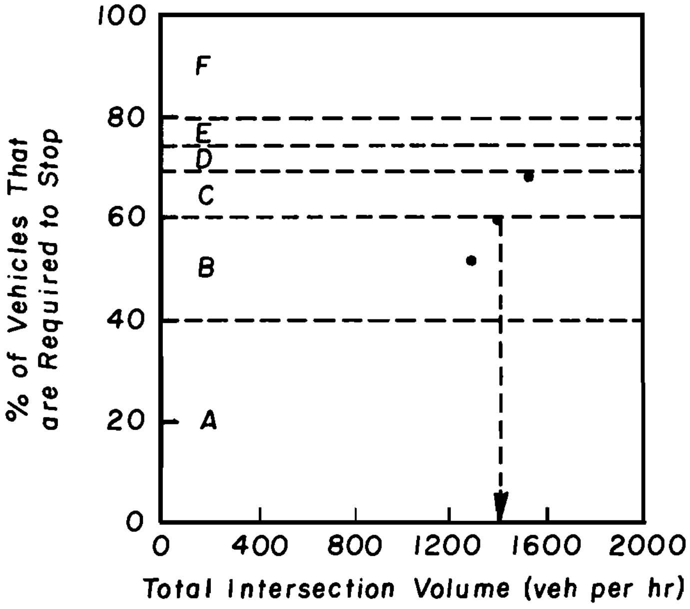


Fig 7. Service volume at Level of Service B for a 2-lane by 2-lane uncontrolled intersection.

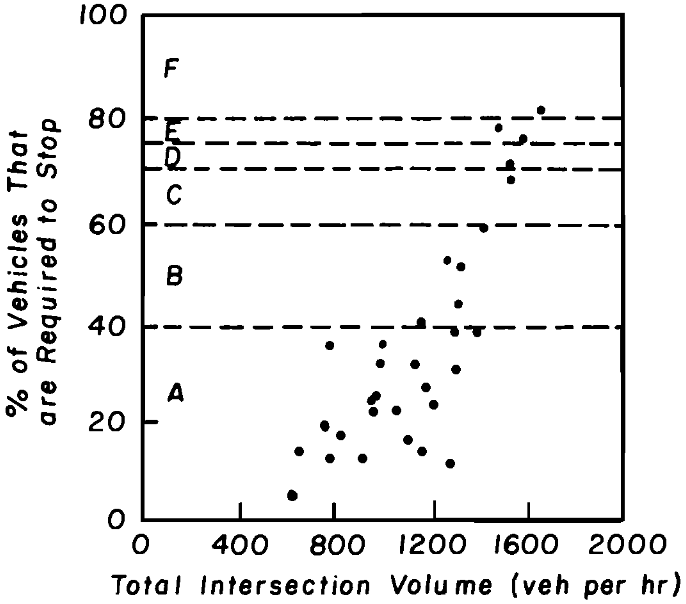


Fig 8. Analysis of a 2-lane by 2-lane uncontrolled intersection.

TABLE 5. RELATIONSHIP BETWEEN LEVEL OF SERVICE AND VOLUME FOR A 2-LANE BY 2-LANE UNCONTROLLED INTERSECTION

Level of Service	Percentage of Vehicles Required to Stop	Total Intersection Capacity
A	40	1200 veh/hr
B	60	1400 veh/hr
C	70	1500 veh/hr
D	75	1600 veh/hr
E	>75	>1600 veh/hr

TABLE 6. MATRIX OF LANE CONFIGURATION AND TYPE OF TRAFFIC CONTROL SHOWING LEVEL OF SERVICE FOR A TOTAL INTERSECTION VOLUME OF 1600 VEH/HR

Type of Control	2-Lane Major 2-Lane Minor	2-Lane Major 4-Lane Minor	4-Lane Major 2-Lane Minor	4-Lane Major 4-Lane Minor
Uncontrolled	D	-	-	-
Yield-sign	D or E	-	E	-
Two-way stop	D	B	B	A
All-way stop	E	E	C or D	C

been based on empirical formulae, probability of vehicle spacing, or observation of intersections. The method described here uses a microscopic, demand-responsive simulation model for evaluating the behavior of traffic at intersections with any form of control.

Capacity is the maximum volume that can be accommodated while maintaining a desired level of service. The relationship between capacity and level of service was investigated. Subjectively-defined levels of service were established and qualified by relating them to specified values of selected performance indicators. Performance indicators that were best suited for the various types of intersection control were identified, and the levels of service that can be expected for different values of these performance indicators were determined. Table 3 presents a summary of recommended indicators, and quantitative values, for each level of service and for the various types of traffic control that may be used at unsignalized intersections. Four cases in which the TEXAS Model can be used for determining intersection capacity and level of service are presented as examples. In the first case, the level of service was determined knowing the geometry and type of intersection control. For the second case, the maximum value that can be accommodated at a specified level of service for a given intersection geometry was determined. For the third case, a given intersection geometry was assumed and the maximum volume that can be accommodated at each level of service was determined. In the fourth case, an intersection was designed to accommodate a given volume of traffic while maintaining a specified level of service.

CHAPTER 4. EVALUATION OF TRAFFIC CONTROL WARRANTS

Five basic types of traffic control are generally available for use at intersections: (1) two-way yield, (2) two-way stop, (3) all-way stop, (4) fixed-time signal, and (5) traffic-actuated control. Each of these has its best application under certain conditions of traffic flow. The less restrictive sign control is usually associated with lower traffic volumes; higher volumes usually mandate some type of signal control. The criteria by which intersection control should be selected have long been recognized as an important element of traffic engineering. In recognition of the need for nationwide uniformity of traffic control, an updated version of the Manual on Uniform Traffic Control Devices (Ref 4) was published in 1971, and a new revision is due in 1978. This manual, along with several other publications, suggests warrants for various forms of intersection control.

Application of the TEXAS Model

The TEXAS Model provides a convenient and practical method for investigating the validity of existing traffic-based warrants for intersection control and for examining existing and proposed warrants. In the final phase of Research Study 3-18-72-184, more than 600 simulation runs were made for different types of intersections handling a wide range of traffic volumes under different forms of control. The resulting relationships between geometry, volume, and delay were thoroughly analyzed. These relationships were then used to appraise the validity of several existing warrants and to suggest new traffic signal warrants.

Existing Warrants

Warrants are presented in the Manual on Uniform Traffic Control Devices (MUTCD) (Ref 4) for yield-sign control, stop-sign control, and signal control. Provisions of the signal warrants, which are of most importance in this investigation, are summarized here.

Warrant 1, Minimum Vehicular Volume. This warrant specifies major street and higher-volume minor street approach vehicular volumes for the eighth highest hour of an average day. When these volumes are met or exceeded, a traffic signal may be considered under this warrant. These volumes are shown in Table 7.

Warrant 2, Interruption of Continuous Traffic. This warrant specifies a different set of volumes for the eighth highest hour, as shown in Table 8, and implies conditions under which two-way stop control might be replaced by signal control.

Other warrants for signals are included in the MUTCD, but these two are the only ones which deal with actual traffic volume parameters. Warrant 3, Minimum Pedestrian Volume; Warrant 4, Progressive Movement; Warrant 5, Accident Experience; and Warrant 6, Combination of Warrants, are the other warrants.

TEXAS utilizes MUTCD (Ref 4) warrants for pretimed signals, but also considers traffic actuated signal installations where peak period volumes exceed certain values (Ref 5). The 2-hour graphical warrant appears in Fig 9. Studies by the State Department of Highways and Public Transportation at twenty permanent count stations revealed that the hourly volumes for the fourth and second high hours were approximately 25 percent and 50 percent larger, respectively, than the eighth high hour volumes. In developing the Texas warrants, factors of 1.25, 1.50, and 1.75 were applied to the MUTCD warrant volumes for the fourth, second, and first high hour, respectively. The factor of 1.75 was chosen for use when heavy traffic volumes exist during only one hour of an average day.

Scope of Warrant Investigation

In order to evaluate the volume-based signal warrants, simulation runs using a range of traffic volume from well below to well above those included in the warrants were made. The variety of runs that were made is shown schematically in Fig 10.

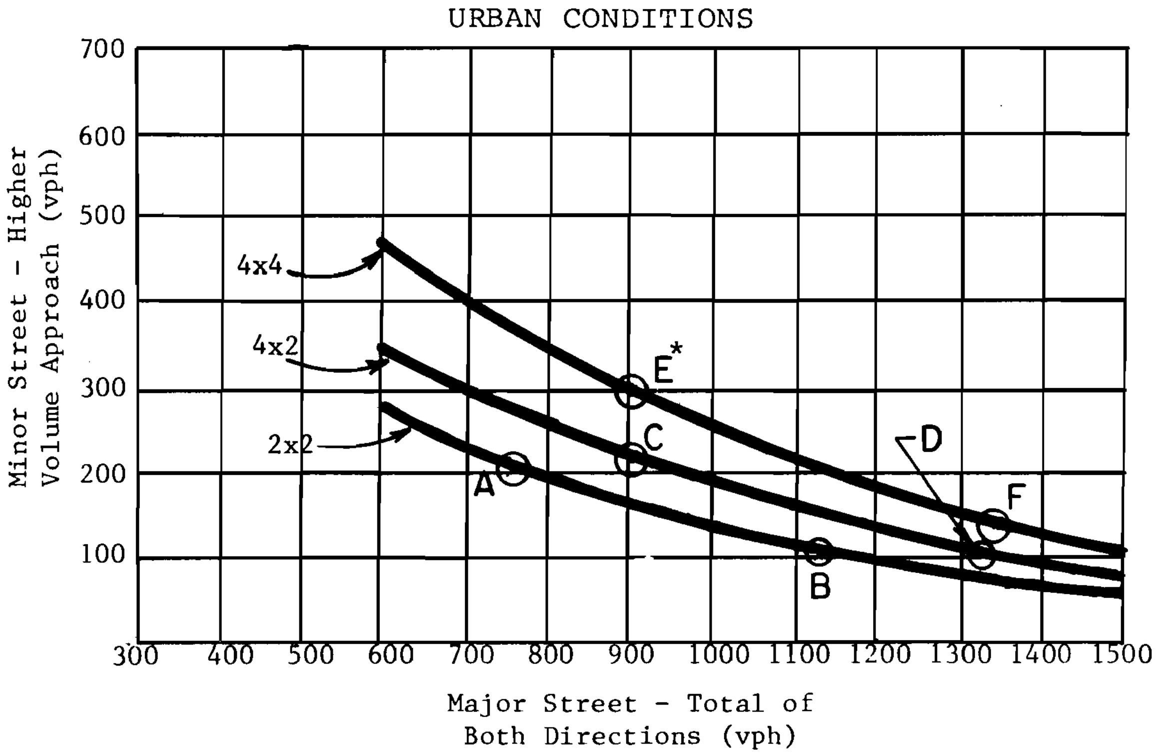
There are three basic inputs to the TEXAS Model: (1) geometry, (2) intersection control, and (3) traffic pattern. Each of these inputs was varied one at a time while the other two were held constant. In this way, a match-up of all the input was included.

TABLE 7. MINIMUM VEHICULAR VOLUMES FOR WARRANT 1 (MUTCD, 1971, p 236)

Number of Lanes for Moving Traffic on Each Street		Vehicles Per Hour on Major Street (Total of Both Approaches)	Vehicles Per Hour on Minor Street (Higher Volume Approach Only)
Major Street	Minor Street		
2	2	500	150
4 or more	2	600	150
2	4 or more	500	200
4 or more	4 or more	600	200

TABLE 8. MINIMUM VEHICULAR VOLUMES FOR WARRANT 2 (MUTCD, 1971, p 237)

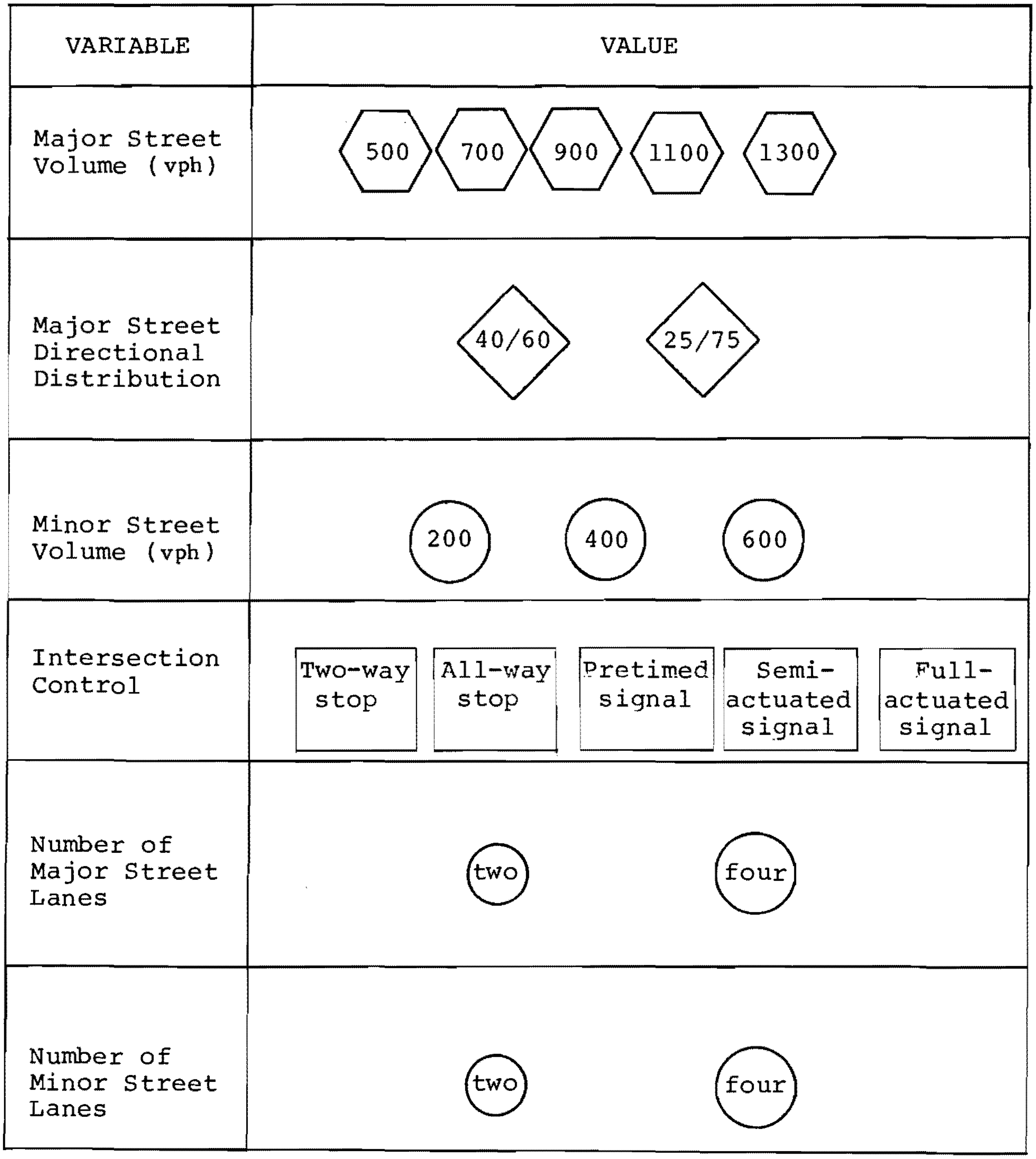
Number of Lanes for Moving Traffic on Each Street		Vehicles Per Hour on Major Street (Total of Both Approaches)	Vehicles Per Hour on Minor Street (Higher Volume Approach Only)
Major Street	Minor Street		
2	2	750	75
4 or more	2	900	75
2	4 or more	750	100
4 or more	4 or more	900	100



[Source: Reference 5]

*See page 62 for reference to points

Fig 9. Texas SDHPT actuated signal warrants, 2nd high hour.



VARIABLE	VALUE
Major Street Volume (vph)	500 700 900 1100 1300
Major Street Directional Distribution	40/60 25/75
Minor Street Volume (vph)	200 400 600
Intersection Control	Two-way stop All-way stop Pretimed signal Semi-actuated signal Full-actuated signal
Number of Major Street Lanes	two four
Number of Minor Street Lanes	two four

Fig 10. Pyramidal representation of 600 runs of the TEXAS Model using 6 levels.

(1) Geometry: Since four geometric configurations, or lane configurations, are contained in the MUTCD warrants, the same four were chosen for simulation:

Number of Lanes for Moving Traffic on Each Street		Shorthand Notation of Configuration
Major Street	Minor Street	
2 lanes	2 lanes	2 × 2
2 lanes	4 lanes	2 × 4
4 lanes	2 lanes	4 × 2
4 lanes	4 lanes	4 × 4

(2) Intersection control: Five basic types of control were used in the investigation - two-way stop on minor street, four-way stop, pretimed signal, semi-actuated signal, and full-actuated signal.

A sixty-second cycle was used for the pretimed controller. An even split of 27 seconds green on each approach was used for most runs. However, when traffic volume became greatly uneven, the split was altered so that the main street would receive 32 seconds of green.

In the case of traffic-actuated control, several loop detector configurations were investigated. These arrangements are shown in Fig 11. Pressure pad detectors were compared with 20-foot, 40-foot, and 80-foot loop detectors. Detectors were placed at the stop line and 40 feet back from the intersection. Almost no difference in signal operation could be seen between 40-foot-long detectors and pressure pad detectors. More max-outs and longer phase time occurred with 80-foot loops when compared to 40-foot loops. As a result of longer phase times, total lost time at the intersection was increased in the range of 25 to 100 percent. Although it appears that shorter loops would have yielded lower delays, later analysis will show that actuated signals gave lower delays than other types of control. Therefore, these higher delays can be viewed as conservative estimates of the best operation of traffic actuated controllers. To be conservative, 80-foot detectors were simulated, leaving about two car lengths for storage. Controller dial settings used for actuated control were 8 seconds initial interval, 2 seconds vehicle interval, and 3 seconds amber clearance. For the semi-actuated controller, the minimum assured green time for the main street was set at 35 seconds. Maximum extension after demand on red was 25 seconds for the minor street, and (for

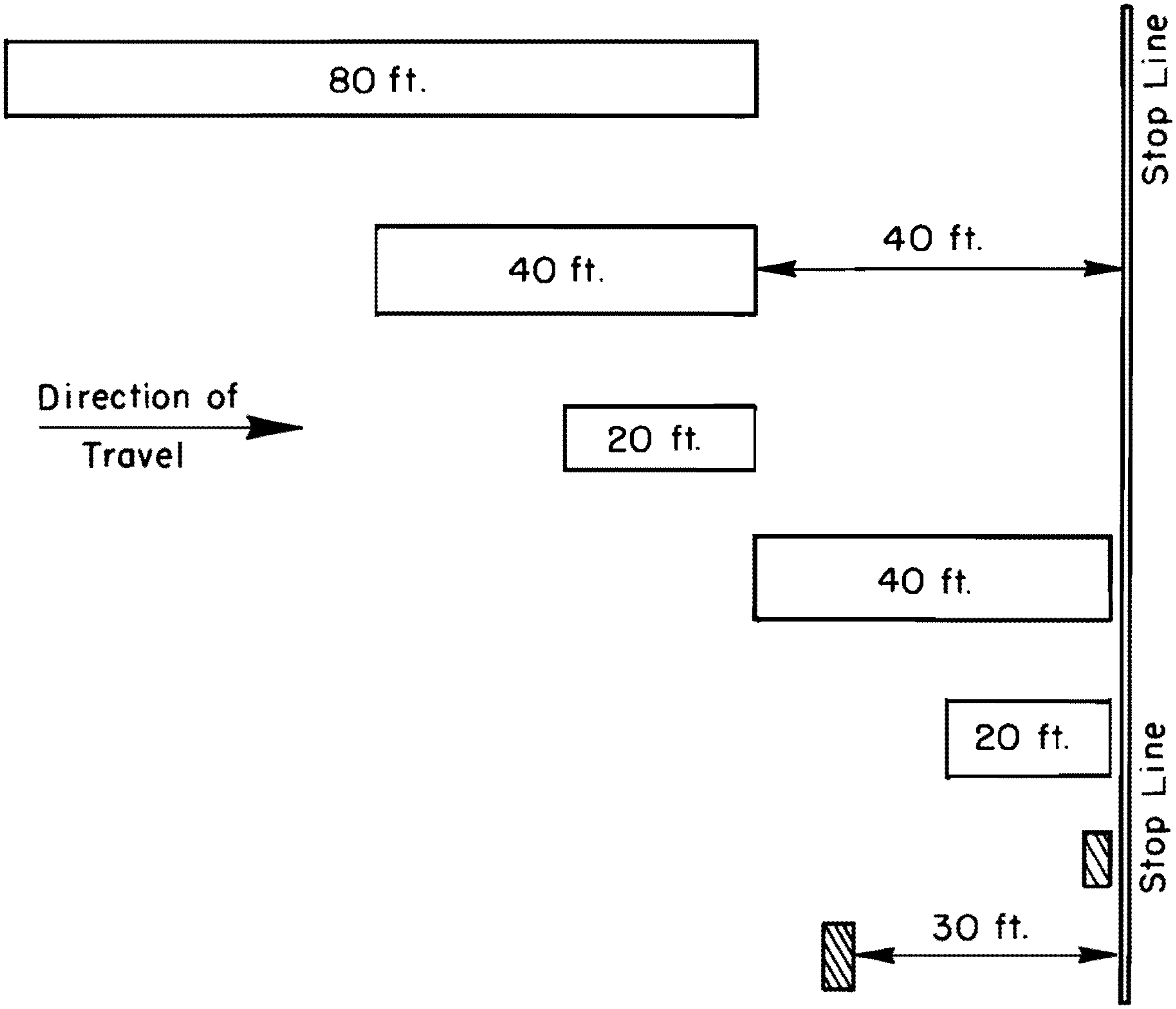


Fig 11. Detector configurations examined.

the full-actuated controller), 45 seconds for the major street. Right turns on red were allowed for all simulation runs.

(3) Traffic demand: A wide range of traffic volumes around those specified in the MUTCD warrants was used. Volumes of 500, 700, 900, 1100, and 1300 vehicles per hour were simulated for the major street. Minor street volumes of 200, 400, and 600 vph were observed. Directional distributions of both 60 percent and 75 percent were used on the major street, and 60 percent alone on the minor street.

(4) Other assumptions:

(a) Turning movements in each approach were held at 10 percent left and 15 percent right.

(b) The distribution used to generate vehicle headways was the Negative Exponential. A further stipulation was that no two vehicles could enter the system on the same lane less than one second apart. In such cases, the trailing vehicle was eliminated.

(c) Two minutes of start-up time and ten minutes of simulation time were used in all cases.

(d) A time-step increment of one second was used for all signalized simulations, but, for non-signalized simulation runs, a time-step of one-half second was used.

(e) Desired speeds for all vehicles entering the system were set as a random variate of the normal distribution.

(f) A mean speed of 30 mph was used and the 85 percentile speed corresponded to the speed limit on all approaches of 35 mph.

The following parameters were varied systematically:

(1) cycle length,

(2) cycle split,

(3) detector design and type,

(4) percent of left-turners, and

(5) right turn on red.

Results of Simulation

Figure 12 shows the relationship between volume and the overall average queue or stopped delay occurring in each approach. When the minor street approach volumes reach about 500 vph under two-way stop control, overall average delays begin to increase rapidly. At approach volumes near 600 vph, all-way

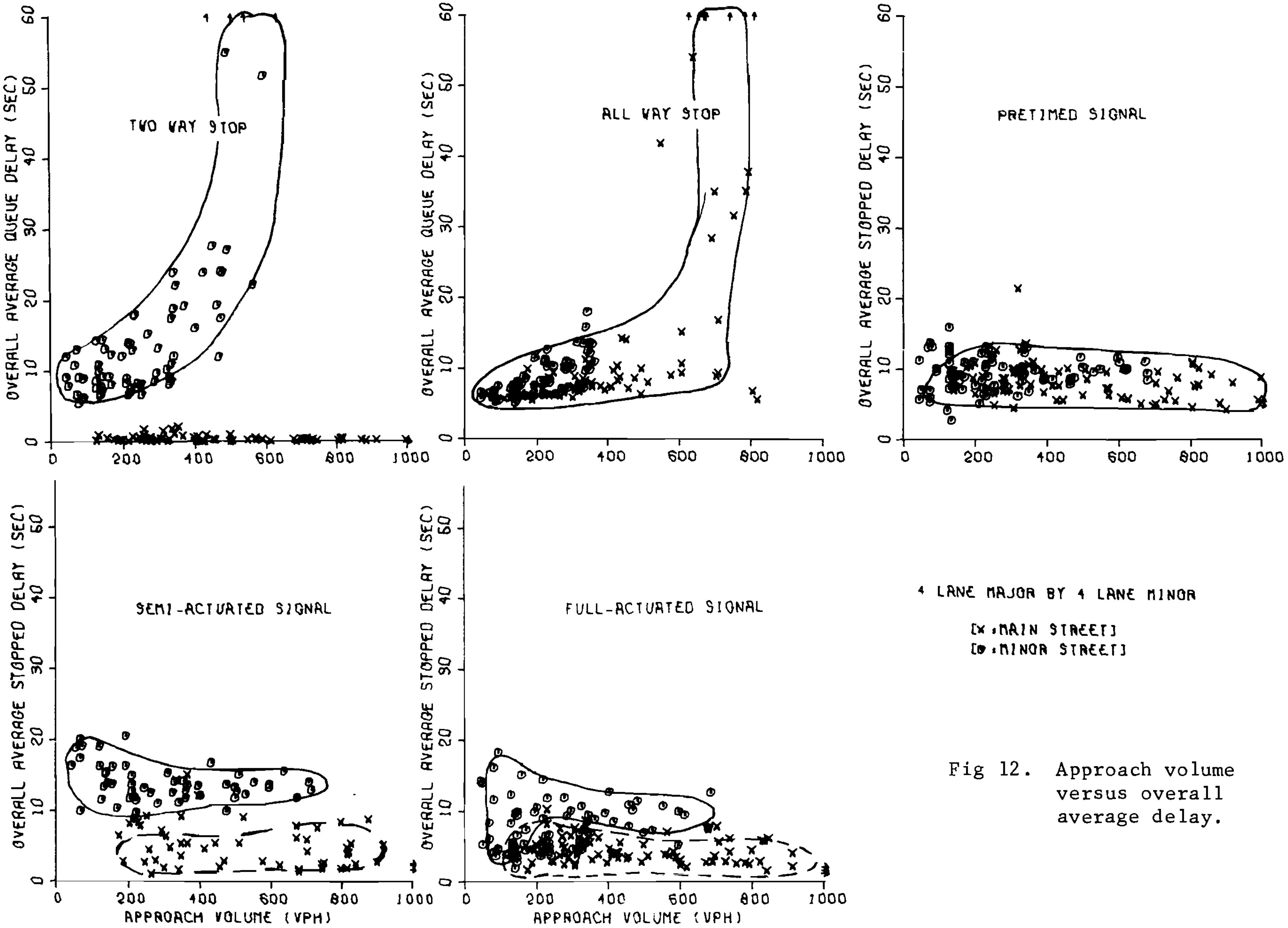


Fig 12. Approach volume versus overall average delay.

stop control begins to show the same tendencies. Table 9 shows the apparent capacity levels for two-way and four-way stops.

Figure 13 relates volume and average delay per delayed vehicle for the total intersections. Figures 12 and 13 consider the 4 × 4 case. Similar figures for the other three cases have been drawn (see Appendix, pp 73-78). An implied criterion is that no one driver is more important than another and that any delay which is incurred should be apportioned fairly among all users. In other words, no driver should find himself being "unreasonably" delayed simply because he is on the minor street. Many traffic engineers and researchers have tacitly adopted a 60-second value as the basis for unreasonable delay. In the case of a 4 × 4 lane configuration, this point is reached at approximately 2000 vph for the two-way stop and 1500 vph for the all-way stop. Table 10 summarizes the corresponding volumes for each of the lane configurations.

Evaluation of Existing Warrants

An examination of the MUTCD signal warrants with respect to the preliminary volume-delay relationships from simulation has shown no obvious inadequacy in the warrants. Volume warrants for a particular type of traffic control are meant to identify the approximate traffic conditions at which a less restrictive means of traffic control should be replaced by a more restrictive means. The reason for the change may be for safety, intersection efficiency and capacity, vehicular delay, or some combination of these. For example, a logical reason to specify yield-sign control is to more safely assign the right-of-way to one of the traffic streams. On the other hand, a traffic signal would probably be specified for reasons of additional capacity or lowered delay.

The most frequently-applied warrants for traffic signals are volume based; that is, the approximate traffic conditions above which a traffic signal is better are specified in terms of the vehicular volume which uses the street. Such warrants are probably utilized because of the fact that volumes are easily measured in the field and apparently serve as an independent variable which measures intersection performance.

More important from the standpoint of justification or evaluation of the warrants, though, is the philosophy which was followed in developing the warrant. Some of the points of view which must be kept in mind are

TABLE 9. APPARENT CAPACITY LEVELS FOR 2-WAY AND 4-WAY STOPS

Lane Arrangement Major Minor	2-Way Stop Control Minor Approach Volume	4-Way Stop Control Major Approach Volume	4-Way Stop Control Minor Approach Volume
4 x 4	500 vph	600 vph	600 vph
4 x 2	150	600	300
2 x 4	600	300	600*
2 x 2	200	300	300

* All-way stop on a 2 × 4 configuration is comparable to an all-way stop on a 4 × 2 configuration, with volumes swapped.

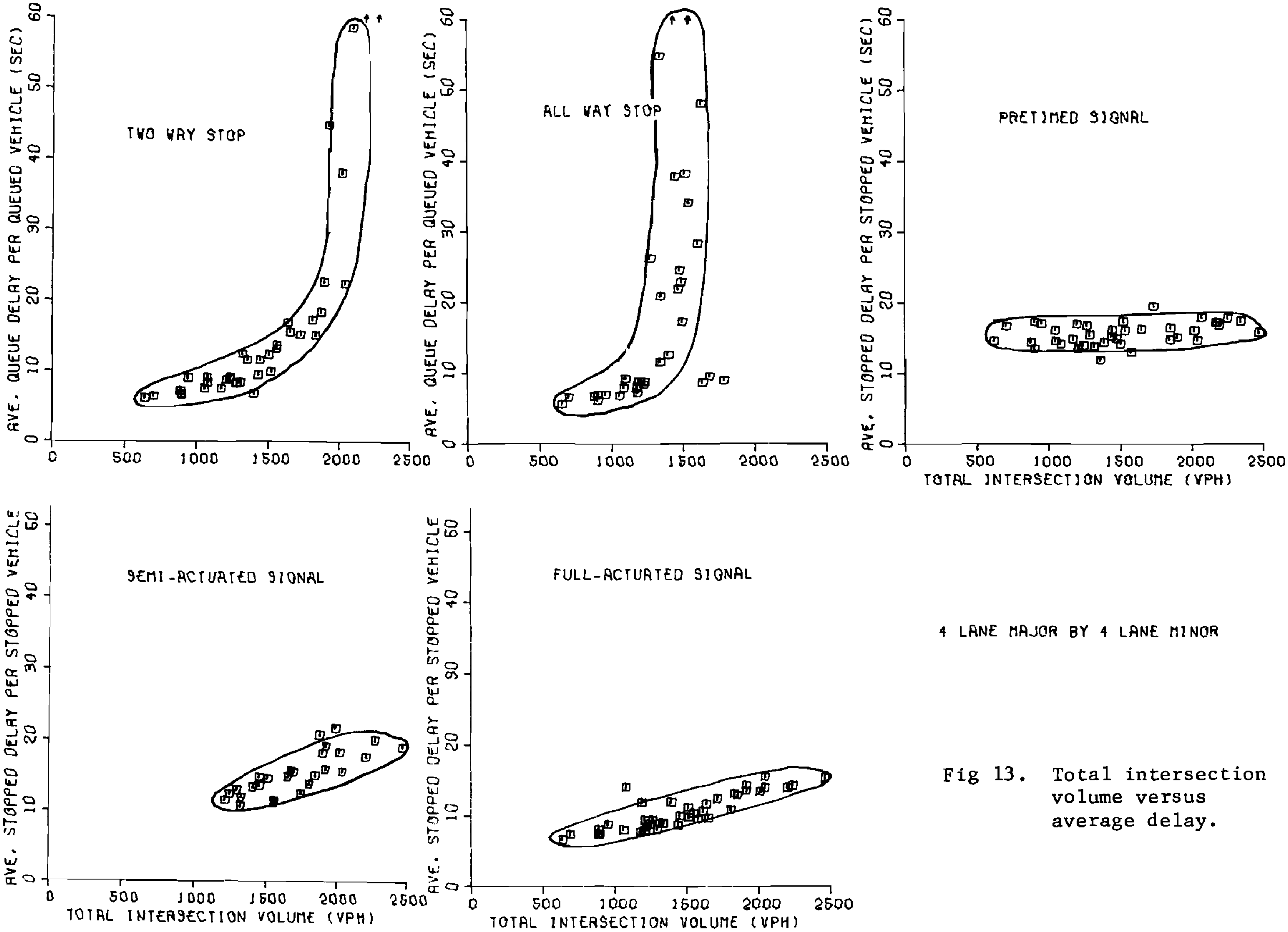


Fig 13. Total intersection volume versus average delay.

TABLE 10. TOTAL INTERSECTION VOLUME WHEN AVERAGE QUEUE DELAY PER QUEUED VEHICLE REACHES 60 SECONDS

Lane Arrangement Major		Minor	Two-Way Stop Control	All-Way Stop Control
4	x	4	2000 vph	1500 vph
4	x	2	1600	1400
2	x	4	1500+	1000
2	x	2	1400	900

(1) least total delay at the intersection,
(2) a balanced delay among approaches,
(3) no unreasonable delays, and
(4) least total cost.

The basis chosen for evaluation of signal warrants in this investigation is least cost.

Cost Concept

The overall cost associated with traffic operations at intersections may be logically considered in terms of user cost and traffic control device (TCD) costs. Each of these two costs may be stated in terms of daily operational costs. Representative values of both user cost and TCD cost may be found in the literature. The development of these costs will now be considered.

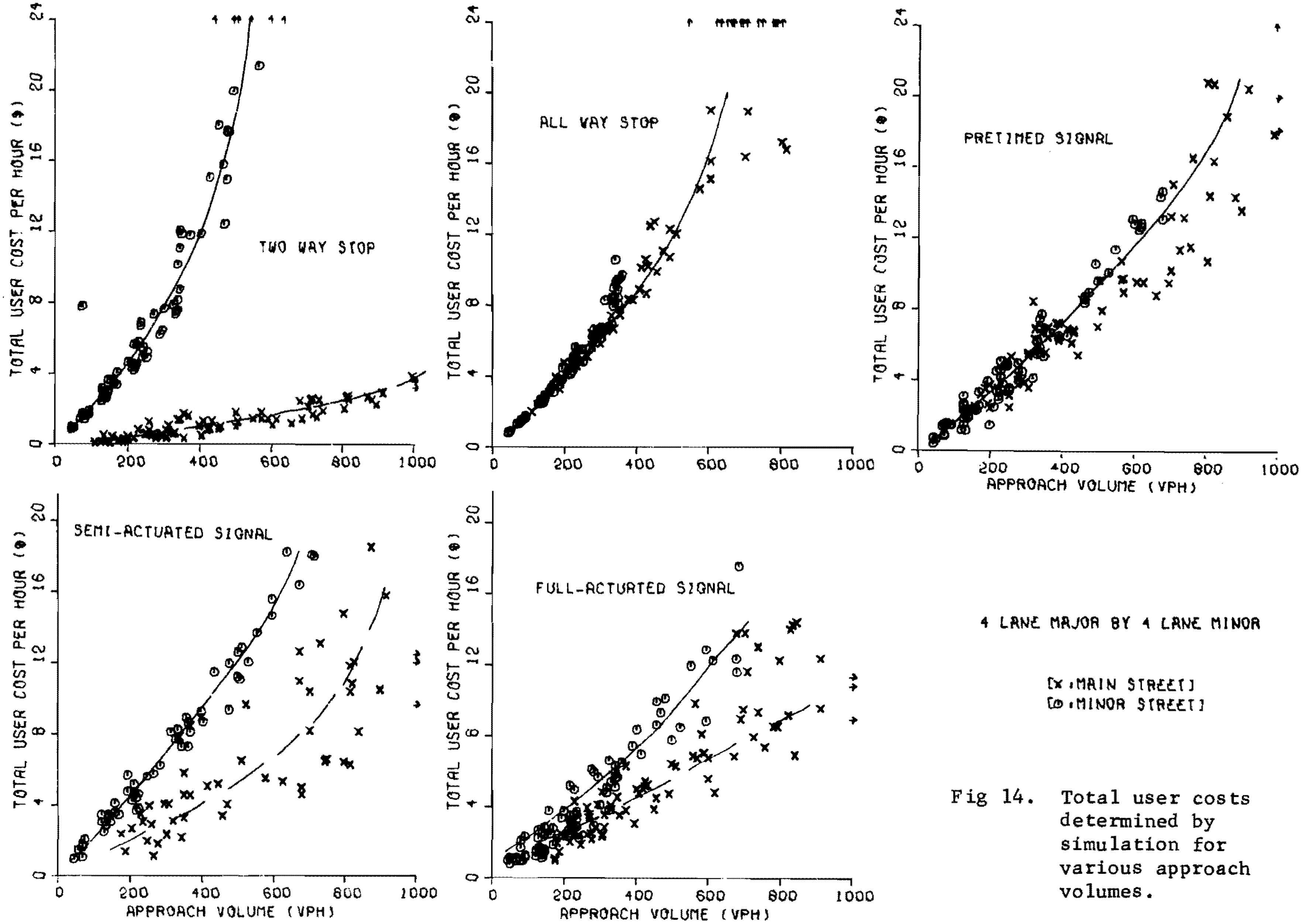
User Cost. User costs, or costs borne by the traffic stream, may be divided into stopping costs and delay costs. Researchers have found that in a single stop-and-go cycle, a vehicle incurs costs in the terms of excess gasoline and lubrication consumption, additional tire wear, increased engine and brake maintenance, and additional depreciation due to wear. Winfrey (Ref 11), in 1952, reported a cost of 0.696 cents per stop from an initial speed of 25 mph. Claffey (Ref 12), in 1971, reported itemized costs of 0.097 gallons of gasoline (0.54 cents if gasoline costs 56 cents per gallon), and between 0.3 cents and 0.6 cents for the other factors for a total of between 0.8 cents and 1.1 cents. These costs were for initial speeds of 25 mph. For purposes of this signal warrant analysis, a cost of one cent is assigned to each vehicle which has to stop.

In additional to actual costs arising from vehicular operation, the value of travel time must be considered. Time saving for commercial vehicles is a direct function of the driver wage and the value of time associated with that particular commercial activity. As such, current estimates of the value of this particular type of time on delay range between $4.00 and $10.00 per hour. In an economic sense, reduction in passenger car travel time is not a saving but certainly is a factor which must be considered. Money is not left unspent, as would occur if gasoline, oil, and tires were not purchased, but time is made available for other purposes. The intersection improvement resulting in travel time reduction would have to be financed by the user spending less money on other commodities rather than the savings realized from commodities he did not have to buy. While some question remains as to the actual value of this time, there is general agreement that drivers are willing to pay for facilities which result in a savings in time. Thomas (Ref 13) cites costs of \$2.80 per hour, and Lisco (Ref 14) reports \$2.50 per hour. Both of these researchers studied the peak hour trip of middle to upper-middle class urbanities in 1966. Winfrey (Ref 11) states that "reasonable values (of time) lie within the range of \$1.00 and \$4.00 per hour, depending on prevailing local factors." At least one researcher has put forward the theory that 10 cars waiting 80 seconds do not have the same economic value associated with waiting that 400 cars waiting 2 seconds would have. Thomas and Thompson (Ref 15) say that the value of time increases faster than the unit of time, so that 2 minutes is worth considerably more than 60 times the value of 2 seconds, the latter being practically valueless. For this signal warrant analysis, a value of \$3.00 per hour will be utilized.

User costs determined by simulation are shown in Figs 14 and 15. The first shows costs experienced in each approach and the second costs for the total intersection. These relationships are for 4 × 4 lane configurations. Similar costs for other lane configurations have been drawn (see Appendix, pp 79-84).

Traffic Control Device Costs. A 1964 study of the economics of signals by Stanford University (Ref 16) reported initial costs of \$8,418 and annual maintenance and operational expenditures (M.O.E.) of \$960 for a typical traffic actuated controller. More recent publications (Ref 17) identify initial construction costs ranging between \$15,000 and \$30,000, depending on the complexity of the intersection, and M.O.E. of \$500 per year. For this warrant analysis, first costs of \$15,000 and M.O.E. of \$1,000 per year will be used for traffic actuated controllers. Pretimed controllers, being less complex, and therefore somewhat less costly, will be assumed to have first costs of \$14,000 and M.O.E. costs of \$800. If the first costs are amortized over a 10-year period using a 7 percent interest rate, a capital recovery factor of 0.1424 results. Therefore, the first costs may be turned into annual costs. A summary of the total annual signal control cost is found in Table 11. Annual costs for sign controlled intersections were ignored since their magnitude is small compared to signal control.

In an economic analysis of signal control, the cost of the control should be "paid for" only during the hours of operation under which it is warranted. Signal control may not be justified during weekend operation, so only 250 days


TWO WAY STOP

ALL WAY STOP

PRETIMED SIGNAL

SEMI-ACTUATED SIGNAL

FULL-ACTUATED SIGNAL

4 LANE MAJOR BY 4 LANE MINOR

[x : MAIN STREET]
[⊙ : MINOR STREET]

Fig 14. Total user costs determined by simulation for various approach volumes.

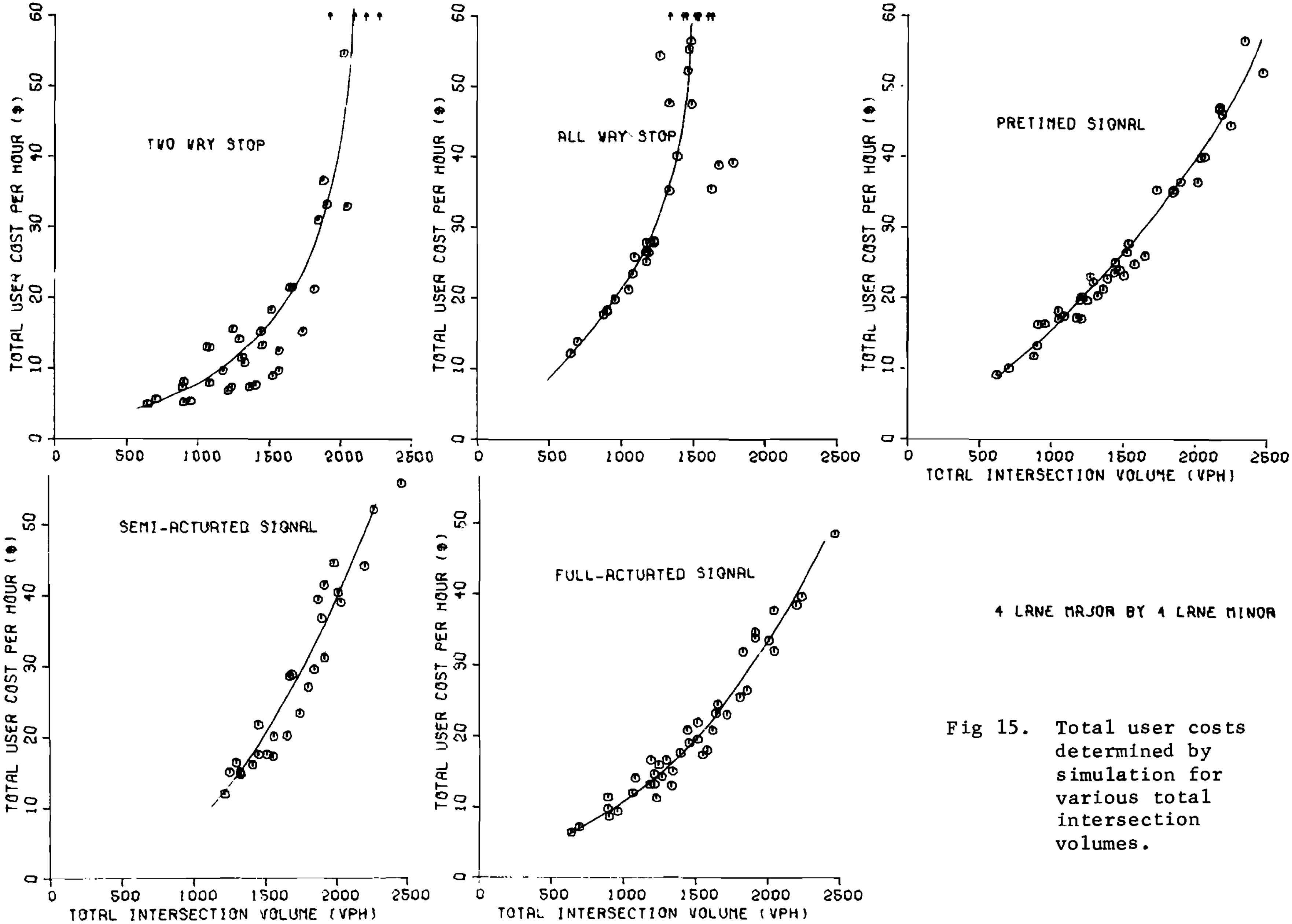


Fig 15. Total user costs determined by simulation for various total intersection volumes.

TABLE 11. ANNUAL SIGNAL COSTS

Signal Type	First Cost	CRF	Equivalent Uniform Annual First Cost	MOE	Total Annual Cost	Total Daily Cost
---at 7% interest over 10 years						
Fixed Time	$11,000	0.1424	$1,566	$800	$2,366	$9.04
Actuated	15,000	0.1424	2,136	1,000	3,136	12.54
---at 10% interest over 10 years						
Fixed Time	11,000	0.1627	1,790	800	2,590	10.36
Actuated	15,000	0.1627	2,440	1,000	3,440	13.76

of the year (weekdays with two peak hours) will be considered. Therefore, the daily costs of signal operation are as shown in Table 11. For a signal to be economically justified then, the user cost associated with signal control must be \$9.00 to \$12.00 per day less than the user cost associated with stop control.

Evaluating Existing MUTCD Warrants

Least Cost Method

Table 12 shows the tabulated results of the total intersection costs for volumes which just meet MUTCD Warrant 1 (minimum vehicular volume) conditions for the 4 × 4 lane configuration (see Appendix, pp 85-87, for other configurations). Table 13 shows similar costs for Warrant 2 (interruption of continuous traffic) conditions (see Appendix, pp 88-90, for other configurations). Costs shown in these tables were obtained in the following manner. Eighth hour volumes were taken directly from the MUTCD Warrants. A slightly uneven directional distibution was assumed for each street, and four volumes, each representing an approach volume, were determined. Using the multiplying factors shown in Table 14 (from Box and Alroth, Ref 18), volumes for the higher hours were obtained. Then, entering the correct graph in Fig 14 with each volume, a user cost was obtained. Similar tables for other lane configurations have been prepared (see Appendix). A summary of all costs for the existing MUTCD Warrants is shown in Table 15.

Several observations concerning the cost results in Table 15 may be made:

(1) Two-way stop control is the least costly for each condition.
(2) All-way stop control is the most costly for each condition.
(3) Traffic actuated signal control is less costly than pretimed for each condition.

Increasing Cost →

Two-way stop control ... Actuated signal control ... Pretimed signal control ... All-way stop control

It appears that, strictly on the basis of cost, the volume levels specified in the MUTCD signal warrants might need adjustment. When considering the replacement of a two-way stop with a signal, warrant volumes should be

TABLE 12. COMPUTED INTERSECTION USER COST TO MEET MUTCD WARRANT 1

Hour	Major Approach Volumes		Minor Approach Volumes		Major Street User Cost					Minor Street User Cost				
	EB	WB	NB	SB	2-Way Stop	4-Way Stop	Fixed-Time Signal	SA* Signal	FA** Signal	2-Way Stop	4-Way Stop	Fixed-Time Signal	SA* Signal	FA** Signal
8	325		200		0.75	7.10	5.00	3.00	3.50	4.25	3.50	3.25	4.40	3.70
		275		150	0.50	5.10	4.30	2.25	2.90	3.00	2.50	2.30	3.25	2.60
7	335		226		0.75	7.25	5.25	3.00	3.55	5.25	4.30	3.50	4.80	4.10
		283		170	0.55	5.80	4.75	2.25	2.90	3.80	2.90	2.50	3.55	3.00
6	365		230		0.80	7.45	5.75	3.25	3.70	5.30	4.50	3.55	4.85	4.15
		308		172	0.60	6.15	5.00	2.60	3.00	3.80	3.00	2.60	3.60	3.00
5	365		254		0.85	7.45	5.75	3.25	3.70	5.90	4.80	4.00	5.30	4.25
		308		190	0.60	6.15	5.00	2.60	3.00	4.20	3.40	3.00	4.10	3.35
4	367		288		0.85	7.50	5.80	3.30	3.70	7.00	5.70	4.60	6.00	5.00
		310		216	0.70	6.20	5.05	2.70	3.00	4.50	4.25	3.30	4.50	3.90
3	390		330		0.90	8.00	6.25	3.50	4.00	8.50	6.90	5.30	7.50	5.50
		330		247	0.75	6.80	5.30	3.00	3.50	5.40	5.00	4.00	5.30	4.30
2	432		370		1.00	8.80	7.00	4.10	4.50	10.00	8.00	6.00	8.00	6.00
		365		277	0.80	7.50	6.00	3.25	3.70	6.50	5.60	4.50	5.80	4.70
Peak	432		408		1.00	8.80	7.00	4.10	4.50	11.75	8.75	6.50	9.00	7.00
		365		306	0.80	7.50	6.00	3.25	3.70	7.50	6.20	5.00	6.70	5.15
Sum					12.90	113.60	89.20	49.40	56.80	96.60	90.40	63.90	86.60	69.70

Total Intersection User Cost, 8-Hour Totals	2-Way Stop	4-Way Stop	Fixed-Time Signal	SA* Signal	FA** Signal
	109.50	204.00	153.10	143.40	126.50

4 x 4 Geometry

Warrant 1 Conditions

*SA = Semi-actuated
**FA = Full-actuated

TABLE 13. COMPUTED INTERSECTION USER COST TO MEET MUTCD WARRANT 2

Hour	Major Approach Volumes		Minor Approach Volumes		Major Street User Cost					Minor Street User Cost				
	EB	WB	NB	SB	2-Way Stop	4-Way Stop	Fixed-Time Signal	SA* Signal	FA** Signal	2-Way Stop	4-Way Stop	Fixed-Time Signal	SA* Signal	FA** Signal
8	500		100		0.80	11.25	8.20	5.00	5.40	2.00	1.75	2.00	2.10	2.00
		400		75	0.60	8.50	6.50	3.90	4.25	1.30	1.25	1.60	1.70	1.60
7	515		113		1.00	12.00	8.50	5.25	5.70	2.30	2.00	2.10	2.40	2.20
		412		85	0.70	8.75	6.80	4.00	4.50	1.50	1.30	1.60	1.80	1.75
6	560		115		1.05	13.00	9.10	5.90	6.00	2.35	2.00	2.10	2.40	2.20
		448		86	0.75	9.70	7.25	4.50	4.75	1.50	1.30	1.65	1.80	1.75
5	560		127		1.05	13.00	9.10	5.90	6.00	2.50	2.10	2.20	2.70	2.35
		448		95	0.75	9.70	7.25	4.50	4.75	1.60	1.50	1.80	2.00	2.00
4	565		144		1.10	13.25	9.25	6.00	6.00	2.70	2.50	2.30	3.10	2.60
		452		108	0.75	9.80	7.30	4.50	4.80	1.90	1.70	2.10	2.25	2.10
3	600		165		1.25	14.50	10.25	6.75	6.50	3.00	2.80	2.70	3.80	2.90
		480		124	0.85	10.25	7.75	5.00	5.00	2.25	2.00	2.25	2.75	2.20
2	665		185		1.50	18.00	11.25	8.20	7.70	4.00	3.00	3.00	4.00	3.10
		532		135	1.05	12.50	8.60	5.75	5.60	2.50	2.40	2.30	3.00	2.30
Peak	665		204		1.50	18.00	11.25	8.20	7.70	4.50	4.00	3.30	4.25	3.95
		532		153	1.05	12.50	8.60	5.75	5.60	3.00	2.95	2.60	3.25	2.80
Sum					15.75	194.70	136.95	89.10	90.25	38.90	34.55	35.60	43.30	37.80

Total Intersection User Cost, 8-Hour Totals	2-Way Stop	4-Way Stop	Fixed-Time Signal	SA* Signal	FA** Signal
	54.65	229.25	172.55	132.40	128.05

4 x 4 Geometry

Warrant 2 Conditions

*SA = Semi-actuated
**FA = Full-actuated

TABLE 14. RELATIONSHIP BETWEEN EIGHTH HIGH HOUR AND HIGHER HOUR VOLUME

High Hour	Multiplying Factor	
	Major Street	Minor Street
Peak	1.33	2.04
2nd	1.33	1.85
3rd	1.20	1.65
4th	1.13	1.44
5th	1.12	1.27
6th	1.12	1.15
7th	1.03	1.13
8th	1.00	1.00

TABLE 15. SUMMARY OF DAILY COSTS UNDER EXISTING MUTCD WARRANT CONDITIONS

Lane Arrangement	MUTCD Warrant Number	Intersection Traffic Control	User Costs			Traffic Control Device Cost	Total Intersection Cost
			Major Street	Minor Street	Total		
4 x 4	1	2W	12.90	96.90	109.50	0.00	109.50
		4W	113.60	90.40	204.00	0.00	204.00
		PT	89.20	63.90	153.10	9.04	162.14
		SA	49.40	86.60	143.40	12.54	155.94
		FA	56.80	69.70	126.50	12.54	139.04
	2	2W	15.75	38.90	54.65	0.00	54.65
		4W	194.70	34.55	229.25	0.00	229.25
		PT	136.95	35.60	172.55	9.04	181.59
		SA	89.10	43.30	132.40	12.54	132.40
		FA	90.25	37.80	128.05	12.54	128.05
4 x 2	1	2W	16.50	113.65	130.15	0.00	130.15
		4W	122.70	95.80	218.50	0.00	218.50
		PT	95.25	67.75	163.00	9.04	172.04
		SA	51.60	83.25	134.85	12.54	147.39
		FA	65.45	56.05	121.50	12.54	134.04
	2	2W	23.10	36.80	59.90	0.00	59.90
		4W	206.10	34.40	240.50	0.00	240.50
		PT	154.50	24.10	178.60	9.04	187.64
		SA	87.00	39.20	126.20	12.54	138.74
		FA	103.80	27.00	130.80	12.54	143.34
2 x 4	1	2W	12.70	90.65	103.35	0.00	103.35
		4W	103.80	85.65	189.45	0.00	189.45
		PT	75.05	65.75	140.80	9.04	149.84
		SA	45.00	98.90	143.90	12.54	156.44
		FA	54.60	79.70	134.30	12.54	146.84
	2	2W	19.75	38.80	58.85	0.00	58.85
		4W	437.00	40.10	477.10	0.00	477.10
		PT	223.40	27.55	250.95	9.04	259.99
		SA	78.70	44.95	123.65	12.54	136.19
		FA	87.35	34.60	121.95	12.54	134.49
2 x 2	1	2W	16.55	110.60	127.15	0.00	127.15
		4W	179.25	79.15	258.40	0.00	258.40
		PT	109.05	62.70	171.75	9.04	180.79
		SA	53.85	89.75	143.60	12.54	156.14
		FA	67.35	97.15	164.50	12.54	177.04
	2	2W	25.70	34.40	60.10	0.00	60.10
		4W	462.00	34.80	496.80	0.00	496.80
		PT	219.95	25.60	245.55	9.04	254.59
		SA	95.55	34.10	129.65	12.54	142.19
		FA	116.50	38.00	154.50	12.54	167.04

considerably higher than those specified. When, on the other hand, considering the replacement of an all-way stop with a signal, warrant volumes should be considerably lower than those specified.

Proposed Warrants - Cost Basis

The cost associated with all-way stop control (Fig 14) seems to be fairly close to the cost associated with signal control, up to about 200 vehicles per lane per hour. Beyond the volume, four-way stop control costs increase dramatically, and signal control obviously becomes the more cost effective type of intersection control. Under these circumstances, 200 vehicles per lane per hour can be considered to be a critical volume. The following traffic volumes were investigated as possible warrant volumes for the replacement of four-way stop control with signal control.

Cost Analysis of Texas MUTCD Actuated Signal Warrants

The Texas State Department of Highways and Public Transportation supplements the MUTCD signal warrants with a set of graphical warrants for actuated signal control. Four graphs, corresponding to peak hour, second, fourth, and eighth highest hourly volumes, are used. Figure 9 shows a graph for the second high hour. Insofar as the warrant is specified as a continuous function between major street volume and higher-minor-approach minor street volume for various lane arrangements, two points were chosen to represent each lane configuration in the evaluation. The cost associated with each type of control for each of the six traffic conditions are shown in Tables 16, 17, and 18.

Two-way stop control results in the least costly control and four-way stop control is most costly in terms of total intersection costs for each of the six traffic conditions. As concluded in the previous section, a single signal warrant specifying the replacement of either two-way stop or all-way stop control cannot be stated when the basis for the warrant is cost. Rather, signal control is cost warranted over four-way stop control for most traffic conditions. Two-way stop control, while being the most cost effective over a wide range of conditions, must be replaced by signal control when side street delays become excessive.

The concept of having separate or enumerated warrants for signal control has merit. For every traffic condition studied in this report, actuated

TABLE 16. COMPUTED INTERSECTION USER COST

Hour	Major Approach Volumes		Minor Approach Volumes		Major Street User Cost					Minor Street User Cost				
	EB	WB	NB	SB	2-Way Stop	4-Way Stop	Fixed-Time Signal	SA* Signal	FA** Signal	2-Way Stop	4-Way Stop	Fixed-Time Signal	SA* Signal	FA** Signal
POINT A														
2	450		225		1.90	50.00	14.50	6.80	7.60	7.20	5.90	4.30	6.30	7.30
		300		150	1.10	18.00	7.50	3.50	4.80	3.50	3.30	2.50	3.80	4.00
Peak	450		225		1.90	50.00	14.50	6.80	7.60	7.20	5.90	4.30	6.30	7.30
		300		150	1.10	18.00	7.50	3.50	4.80	3.50	3.30	2.50	3.80	4.00
Sum					6.00	136.00	44.00	20.60	24.80	21.40	18.40	13.60	20.20	22.60
POINT B														
2	650		113		3.10	90.00	50.00	11.50	13.00	2.10	2.40	1.60	2.80	2.60
		475		75	1.95	90.00	16.00	7.30	8.20	1.40	1.50	0.80	1.30	1.40
Peak	650		113		3.10	90.00	50.00	11.50	13.00	2.10	2.40	1.60	2.80	2.60
		475		75	1.95	90.00	16.00	7.30	8.20	1.40	1.50	0.80	1.30	1.40
Sum					10.10	360.00	132.00	37.60	42.40	7.00	7.80	4.80	8.20	8.00

Total Intersection User Cost, 2-Hour Totals	2-Way Stop	4-Way Stop	Fixed-Time Signal	SA* Signal	FA** Signal
POINT A	27.40	154.40	57.60	40.80	47.40
POINT B	17.10	367.80	136.80	45.80	50.40

2 x 2 Geometry

Points A and B on Figure 9

*SA = Semi-actuated
**FA = Full-actuated

TABLE 17. COMPUTED INTERSECTION USER COST

Hour	Major Approach Volumes		Minor Approach Volumes		Major Street User Cost					Minor Street User Cost				
	EB	WB	NB	SB	2-Way Stop	4-Way Stop	Fixed-Time Signal	SA* Signal	FA** Signal	2-Way Stop	4-Way Stop	Fixed-Time Signal	SA* Signal	FA** Signal
POINT C														
2	550		225		1.60	13.60	9.40	6.20	7.20	8.00	6.50	5.00	6.10	4.20
		350		150	0.90	7.50	6.00	3.30	4.10	4.00	3.50	3.00	3.80	2.60
Peak	550		225		1.60	13.60	9.40	6.20	7.20	8.00	6.50	5.00	6.10	4.20
		350		150	0.90	7.50	6.00	3.30	4.10	4.00	3.50	3.00	3.80	2.60
Sum					5.00	42.20	30.80	19.00	22.60	24.00	20.00	16.00	19.80	13.60
POINT D														
2	750		113		3.30	25.00	15.10	9.30	10.30	2.60	2.20	1.60	2.40	1.70
		600		75	1.80	15.50	11.70	7.00	8.00	1.60	1.60	0.95	1.90	1.10
Peak	750		113		3.30	25.00	15.10	9.30	10.30	2.60	2.20	1.60	2.40	1.70
		600		75	1.80	15.50	11.70	7.00	8.00	1.60	1.60	0.95	1.90	1.10
Sum					10.20	81.00	53.60	32.60	36.60	8.40	7.60	5.10	8.60	5.60

Total Intersection User Cost, 2-Hour Totals	2-Way Stop	4-Way Stop	Fixed-Time Signal	SA* Signal	FA** Signal
POINT C	29.00	62.20	46.80	38.80	36.20
POINT D	18.60	88.60	58.70	41.20	42.20

4 x 2 Geometry

Points C and D on Figure 9

*SA = Semi-actuated
**FA = Full-actuated

TABLE 18. COMPUTED INTERSECTION USER COST

Hour	Major Approach Volumes		Minor Approach Volumes		Major Street User Cost					Minor Street User Cost				
	EB	WB	NB	SB	2-Way Stop	4-Way Stop	Fixed-Time Signal	SA* Signal	FA** Signal	2-Way Stop	4-Way Stop	Fixed-Time Signal	SA* Signal	FA** Signal
POINT E														
2	550		300		1.30	12.70	9.30	5.80	6.20	7.30	6.10	5.30	7.00	5.40
		350		200	0.60	7.20	6.00	3.30	3.60	4.20	4.05	3.60	4.50	3.80
Peak	550		300		1.30	12.70	9.30	5.80	6.20	7.30	6.10	5.30	7.00	5.40
		350		200	0.60	7.20	6.00	3.30	3.60	4.20	4.05	3.60	4.50	3.80
Sum					3.80	39.80	30.60	18.20	19.60	23.00	20.30	17.80	23.00	18.40
POINT F														
2	750		150		2.00	30.00	13.50	10.20	8.90	3.00	3.00	3.00	3.40	4.00
		600		100	1.40	14.90	10.30	6.70	6.90	2.00	1.90	1.90	2.10	2.20
Peak	750		150		2.00	30.00	13.50	10.20	8.90	3.00	3.00	3.00	3.40	4.00
		600		100	1.40	14.90	10.30	6.70	6.90	2.00	1.90	1.90	2.10	2.20
Sum					6.80	89.80	47.60	33.80	31.60	10.00	9.80	9.80	11.00	12.40

Total Intersection User Cost, 2-Hour Totals	2-Way Stop	4-Way Stop	Fixed-Time Signal	SA* Signal	FA** Signal
POINT E	26.80	60.10	38.40	41.20	38.00
POINT F	16.80	99.60	57.40	44.80	34.00

4 x 4 Geometry

Points E and F on Figure 9

*SA = Semi-actuated
**FA = Full-actuated

control yielded significantly lower costs than pretimed signal control. Even though the investigation in this report used several assumptions regarding signal timings, traffic-actuated signal control seems to be more cost effective than fixed-time signal control at isolated intersections.

Summary

An evaluation of volume-delay relationships was determined by simulation. After reviewing the philosophy of signal warrants, total intersection cost was chosen as the basis for judging the effectiveness of intersection control. Comprised of costs associated with user delay, vehicular stop-start cycles, and traffic control devices, total intersection costs were derived for the range of conditions simulated. Texas SDHPT actuated signal warrants and MUTCD signal warrants were studied. At traffic levels corresponding to each, a cost analysis of the effectiveness of signal control was made. Based solely on cost and delay, two general conclusions may be drawn from the analysis.

(1) Two-way stop control was the least costly control for all conditions evaluated, but intolerable delays to side street traffic, rather than overall cost efficiency, should be the criteria for signalization in this case.

(2) All-way stop control was the most costly control for all conditions evaluated. Even at very light traffic conditions (350 vph major, 250 vph minor, eighth high hour, 4-lane by 4-lane intersection), signal control proved to be more cost effective. All-way stop control is not justified on the basis of cost.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

This report describes a method of employing the TEXAS Model for Intersection Traffic to determine the capacity of isolated intersections operating under different forms of unsignalized control at various subjectively-defined levels of service and to analyze warrants for traffic signals as recommended by the Manual on Uniform Traffic Control Devices and the Texas State Department of Highways and Public Transportation on the basis of cost effectiveness.

Conclusions

The TEXAS Model can be used to (1) determine the capacity of intersections, (2) evaluate the performance of an intersection, and (3) design an intersection, that is, determine the optimum lane combination and traffic control scheme.

Several other conclusions reached as a result of the total investigation include the following.

(1) Two-way stop control provides the least costly means of intersection control over a wide range of traffic conditions when considering the costs associated with stopping, delay, and traffic control devices.

(2) All-way stop control cannot be justified on the basis of total intersection costs. For all traffic conditions included in this investigation, ranging from well below 100 to over 500 vehicles per hour per lane, signal control consistently yielded lower costs than all-way stop-sign control.

(3) Total delay time experienced at an intersection is approximately 75 percent greater than stopped time delay at the intersection. This relationship may be used to estimate total delay when measurements of stopped-time delay are available from field observations.

(4) For isolated intersections, traffic-actuated signal control is more cost effective than fixed-time signal control. Full-actuated control is generally better than semi-actuated, but semi-actuated signals may be appropriate where relatively steady traffic flow is present on the major street.

Traffic-actuated control, in general, causes a lower percentage of vehicles to stop at the intersection when compared with pretimed control.

(5) The decision to replace two-way stop control with signal control should probably be based on tolerable delay rather than on total intersection costs. The following traffic volumes result in about 60 seconds of average stopped-time delay to traffic on the minor street, and are recommended as peak-hour volume warrants for signals (see Table 19).

(6) The TEXAS traffic simulation model has been shown to be a useful tool for studying intersection performance under a wide range of traffic demands and under various types of intersection control. More than 200 hours of real-time intersection operation were simulated during the course of this investigation.

Recommendations

User costs associated with stopping and delay should be considered when selecting a particular type of intersection control. Even at light traffic volumes (e.g., 600 vph, total of all approaches during the eighth high hour), user costs far outweigh the amortized costs of traffic control devices. Computer simulation models provide a practical means for evaluating, on a cost basis, existing or proposed signal warrants. These models can be used to simulate a wide variety of traffic conditions and summary performance statistics can be produced rapidly at a fraction of the cost of field observation.

The scope of the analysis given in this report is somewhat limited, and further study should be undertaken to strengthen and broaden the basis for the conclusions that are drawn. Parameters which need more study include (1) different detector locations and configurations, (2) different signal controller settings, (3) more geometric arrangements, and (4) one-way streets. The variety of intersection configurations and traffic conditions that can be evaluated is quite broad.

TABLE 19. PROPOSED WARRANT FOR REPLACEMENT OF TWO-WAY STOP WITH SIGNALIZATION

Lane Arrangement			Minor Approach
Major		Minor	Volume
4	x	4	550 vph
4	x	2	250 vph
2	x	4	700 vph
2	x	2	250 vph

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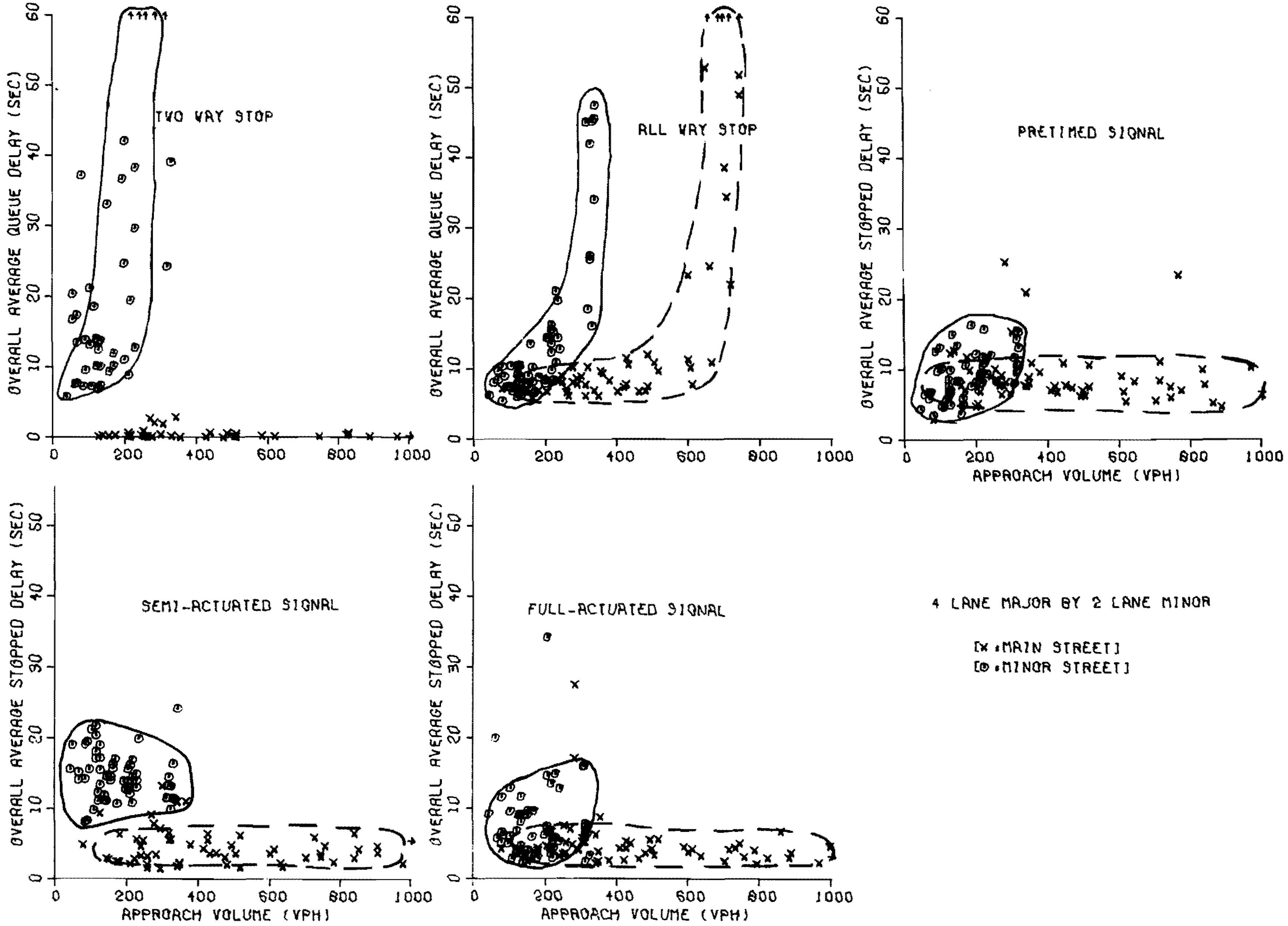
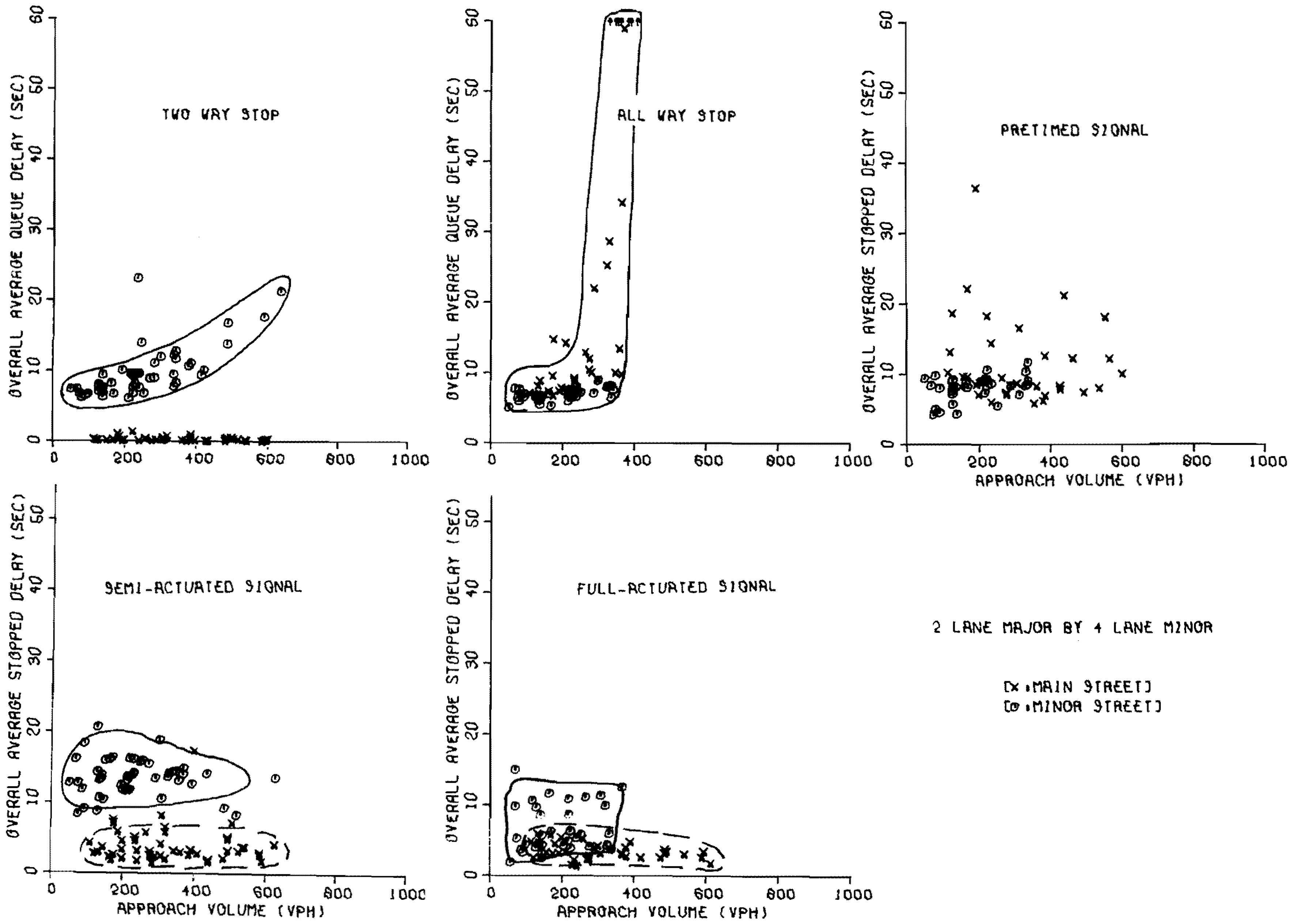
APPENDIX


TWO WAY STOP
ALL WAY STOP
PRETIMED SIGNAL
SEMI-ACTUATED SIGNAL
FULL-ACTUATED SIGNAL
OVERALL AVERAGE QUEUE DELAY (SEC)
OVERALL AVERAGE STOPPED DELAY (SEC)
APPROACH VOLUME (VPH)
0
10
20
30
40
50
60
0
200
400
600
800
1000
4 LANE MAJOR BY 2 LANE MINOR
[x:MAIN STREET]
[⊙:MINOR STREET]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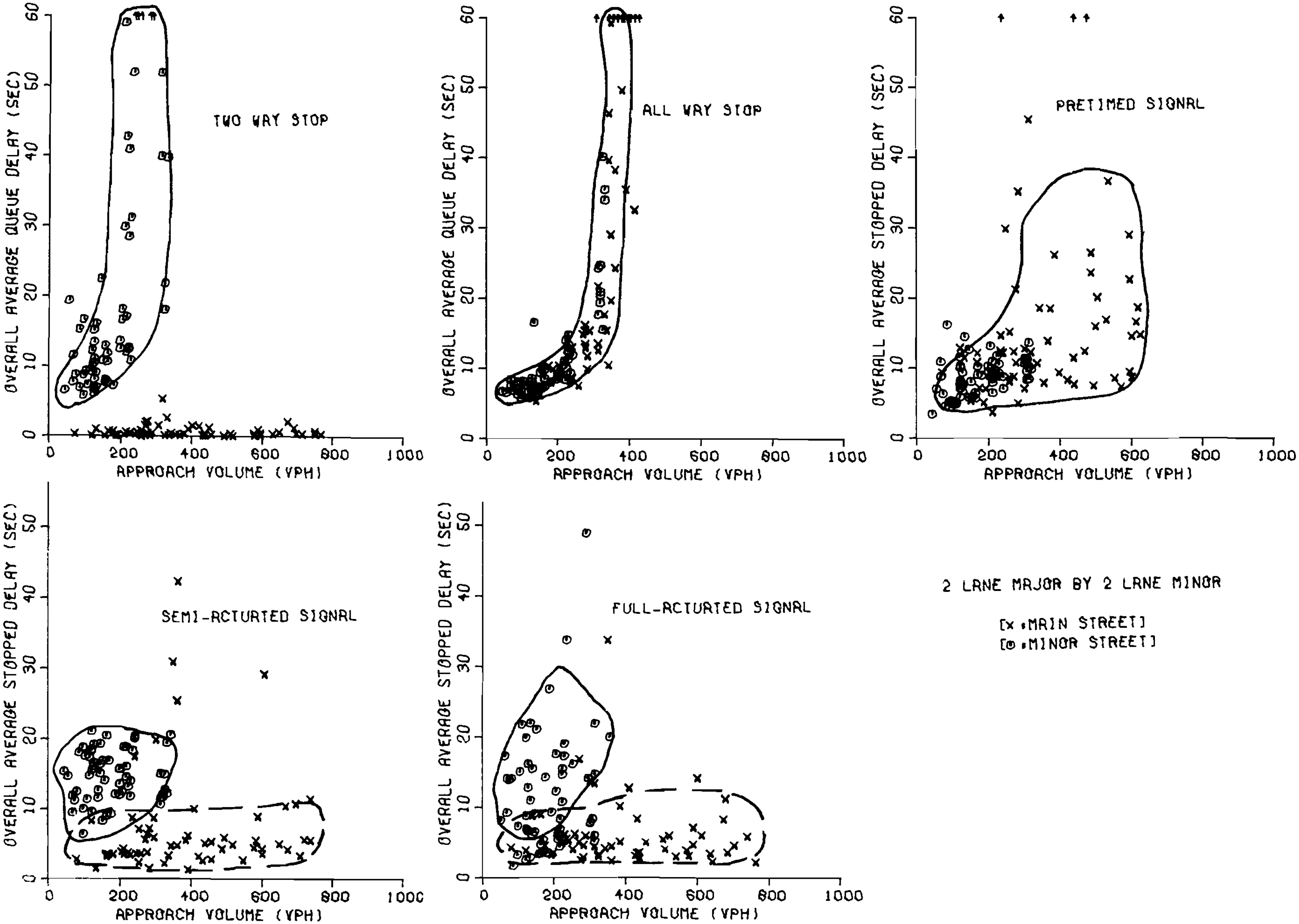
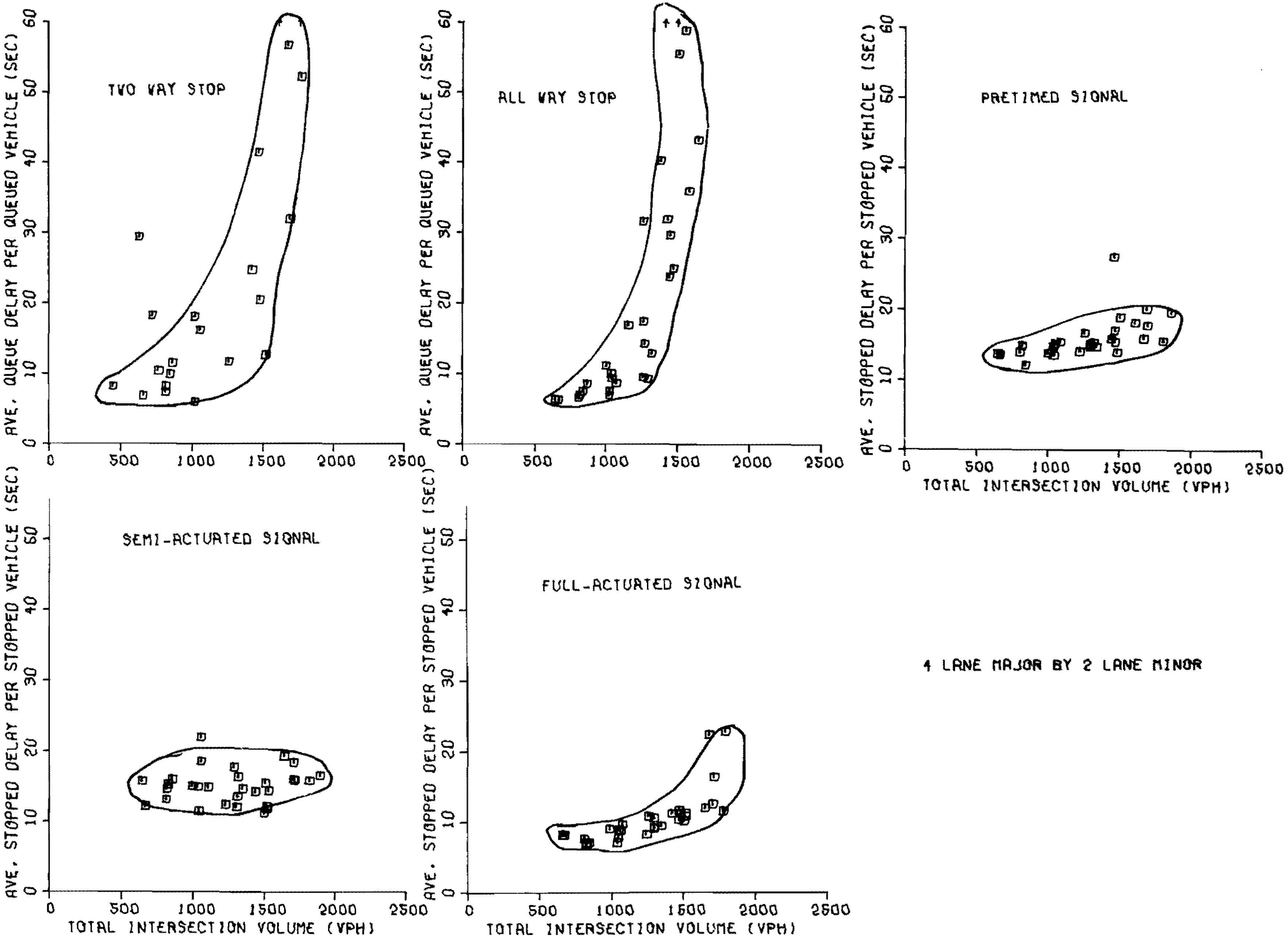
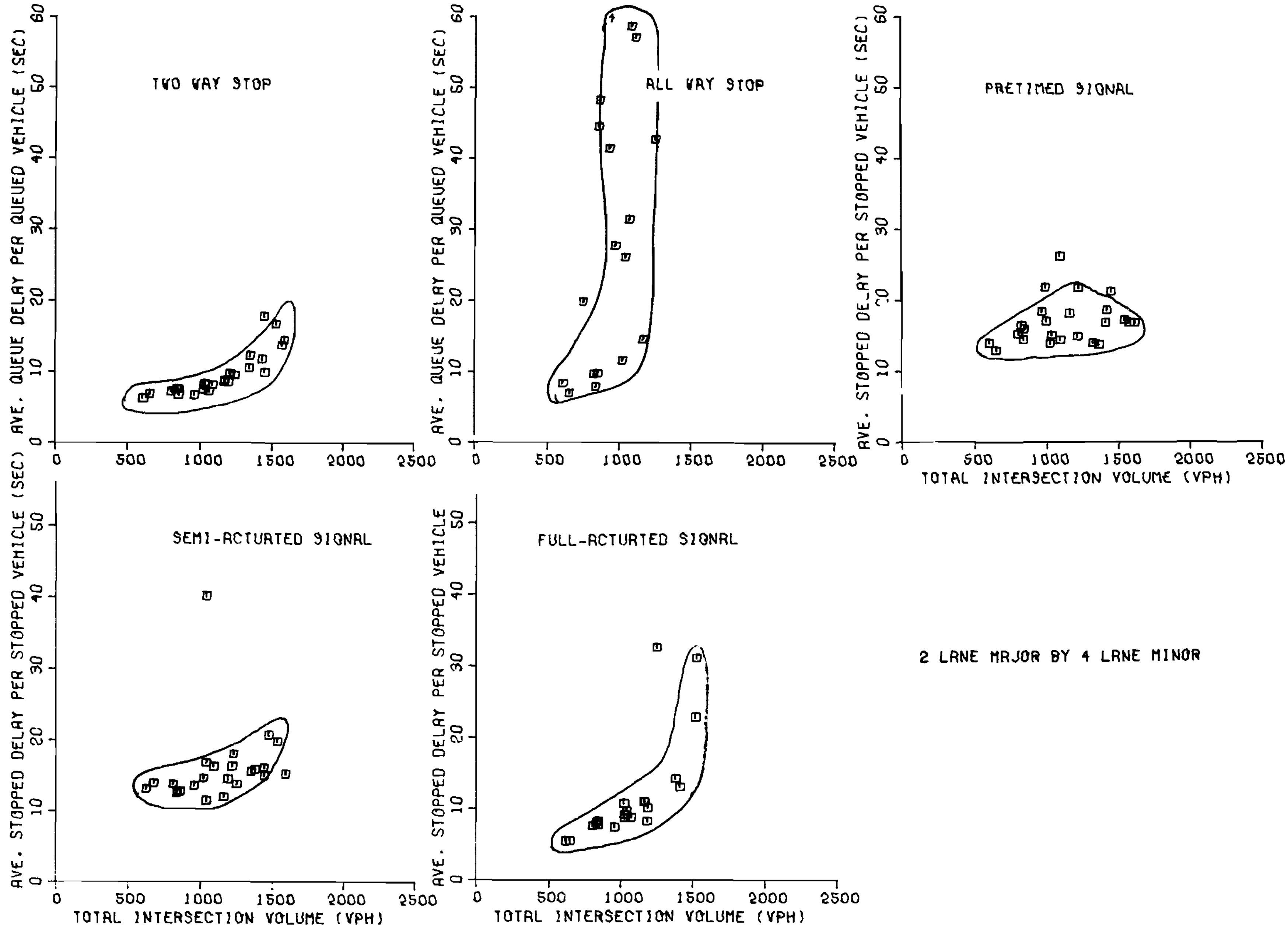
ALL WAY STOP
PRETIMED SIGNAL
SEMI-ACTUATED SIGNAL
FULL-ACTUATED SIGNAL
OVERALL AVERAGE QUEUE DELAY (SEC)
OVERALL AVERAGE STOPPED DELAY (SEC)
APPROACH VOLUME (VPH)
0
10
20
30
40
50
60
0
200
400
600
800
1000
2 LANE MAJOR BY 4 LANE MINOR
[x : MAIN STREET]
[o : MINOR STREET]

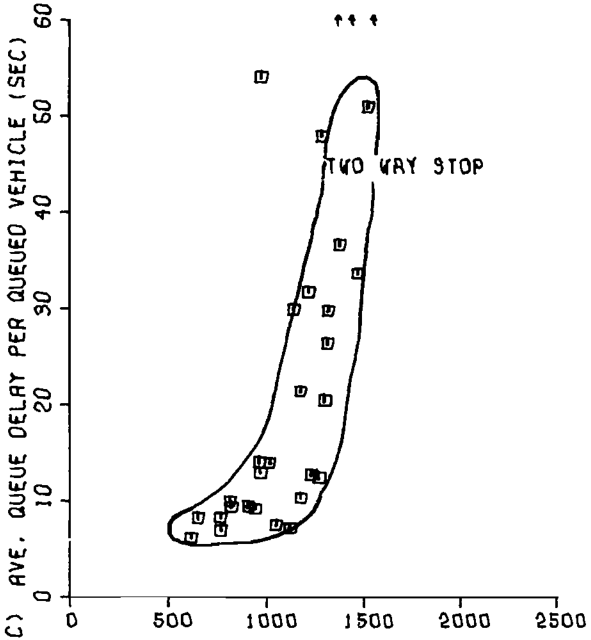

TWO WAY STOP
OVERALL AVERAGE QUEUE DELAY (SEC)
APPROACH VOLUME (VPH)
ALL WAY STOP
OVERALL AVERAGE QUEUE DELAY (SEC)
APPROACH VOLUME (VPH)
PRETIMED SIGNAL
OVERALL AVERAGE STOPPED DELAY (SEC)
APPROACH VOLUME (VPH)
SEMI-ACTUATED SIGNAL
OVERALL AVERAGE STOPPED DELAY (SEC)
APPROACH VOLUME (VPH)
FULL-ACTUATED SIGNAL
OVERALL AVERAGE STOPPED DELAY (SEC)
APPROACH VOLUME (VPH)
0
10
20
30
40
50
60
0
200
400
600
800
1000
2 LANE MAJOR BY 2 LANE MINOR
[x : MAIN STREET]
[⊙ : MINOR STREET]

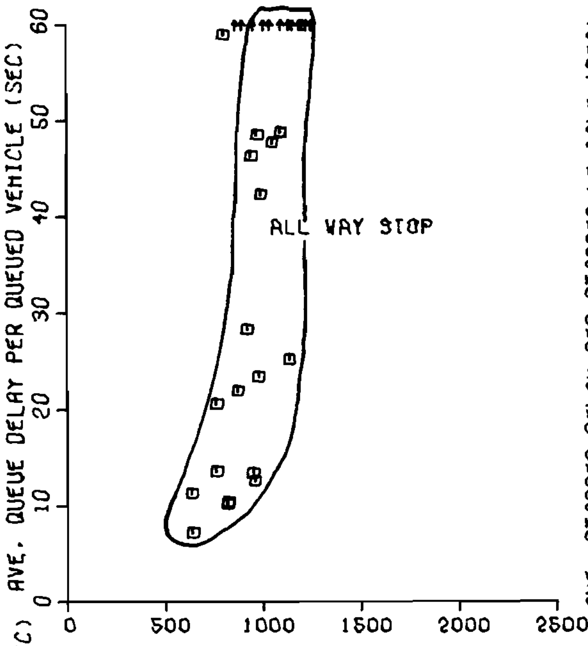


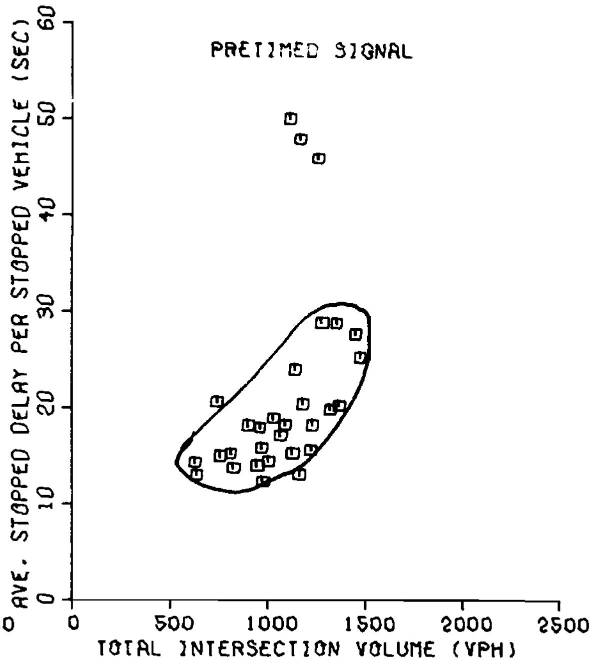
4 LANE MAJOR BY 2 LANE MINOR

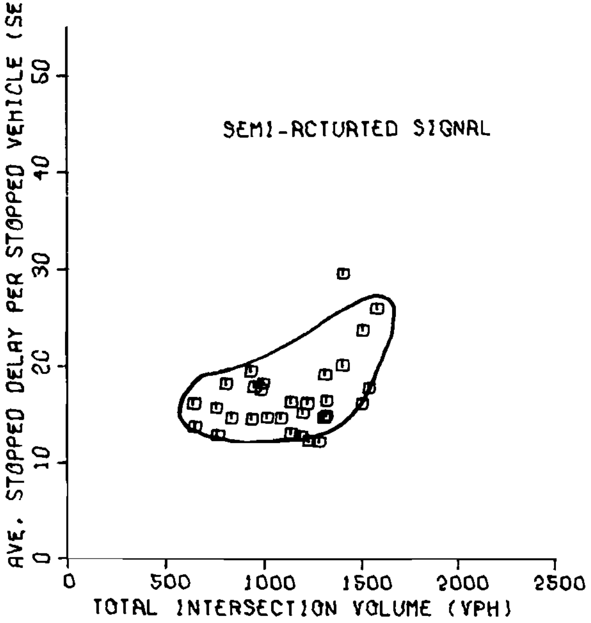


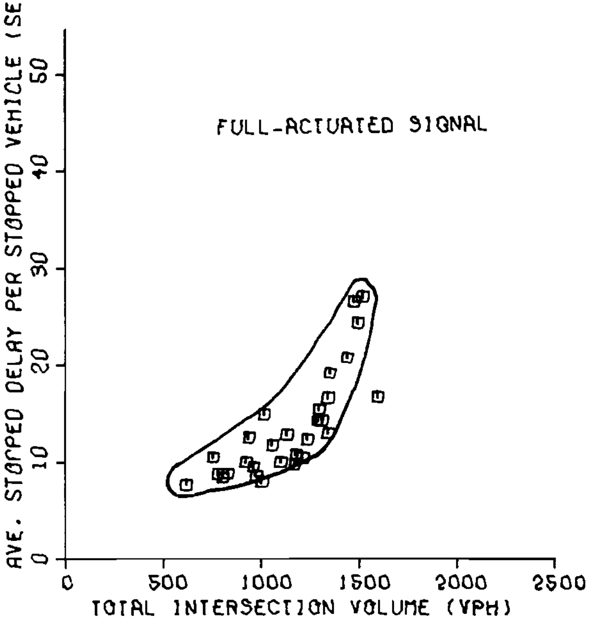
2 LANE MAJOR BY 4 LANE MINOR



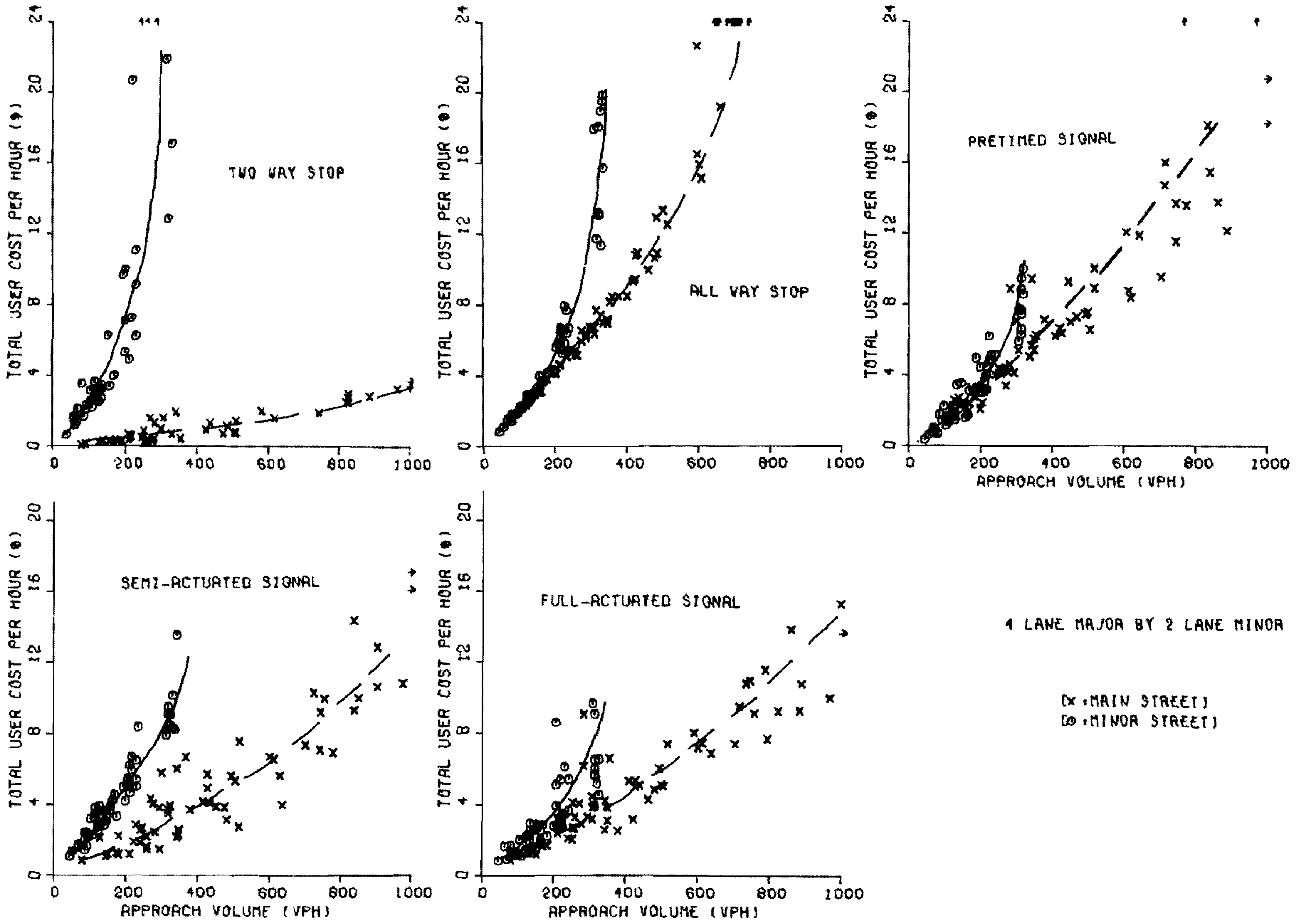


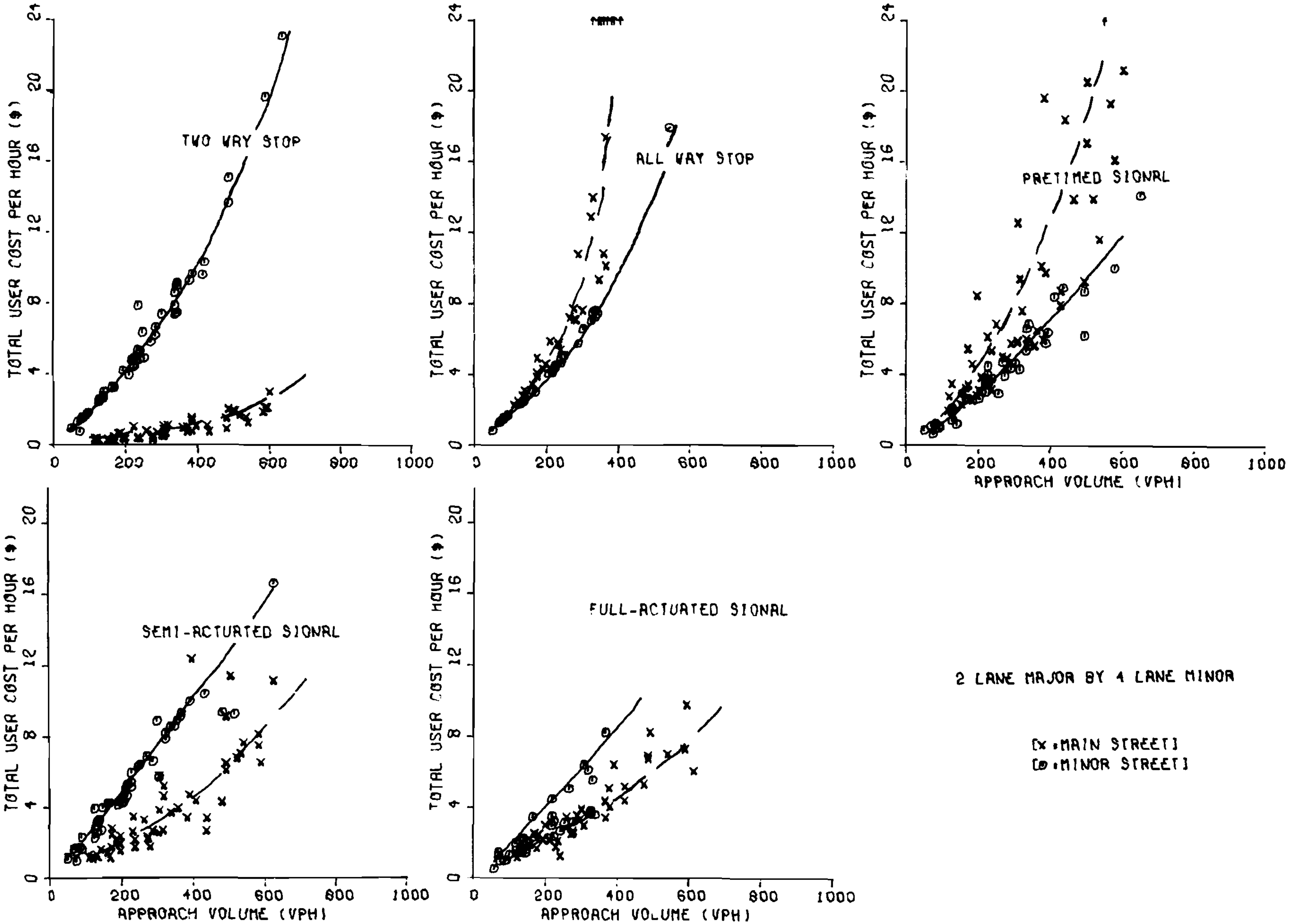


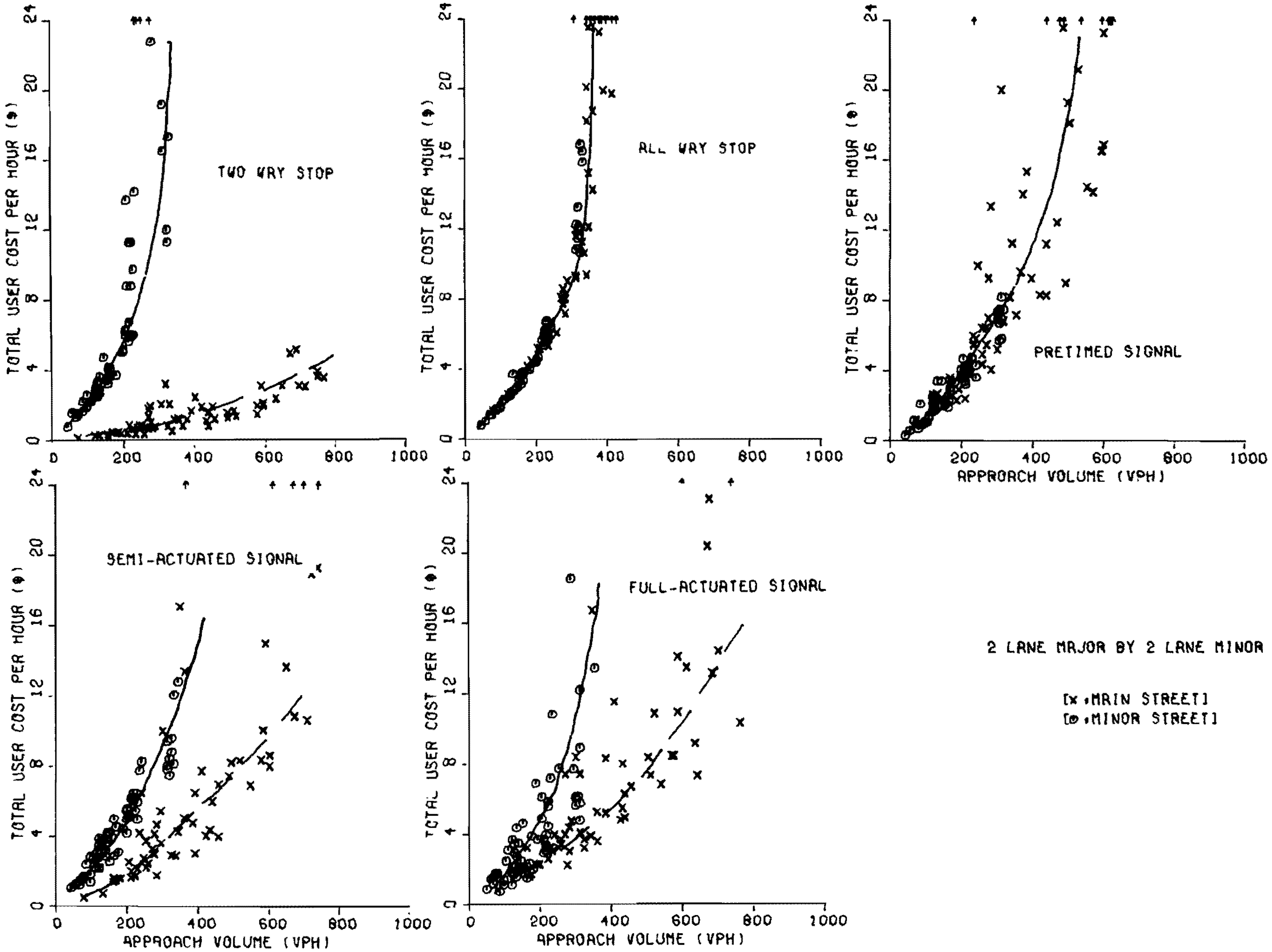


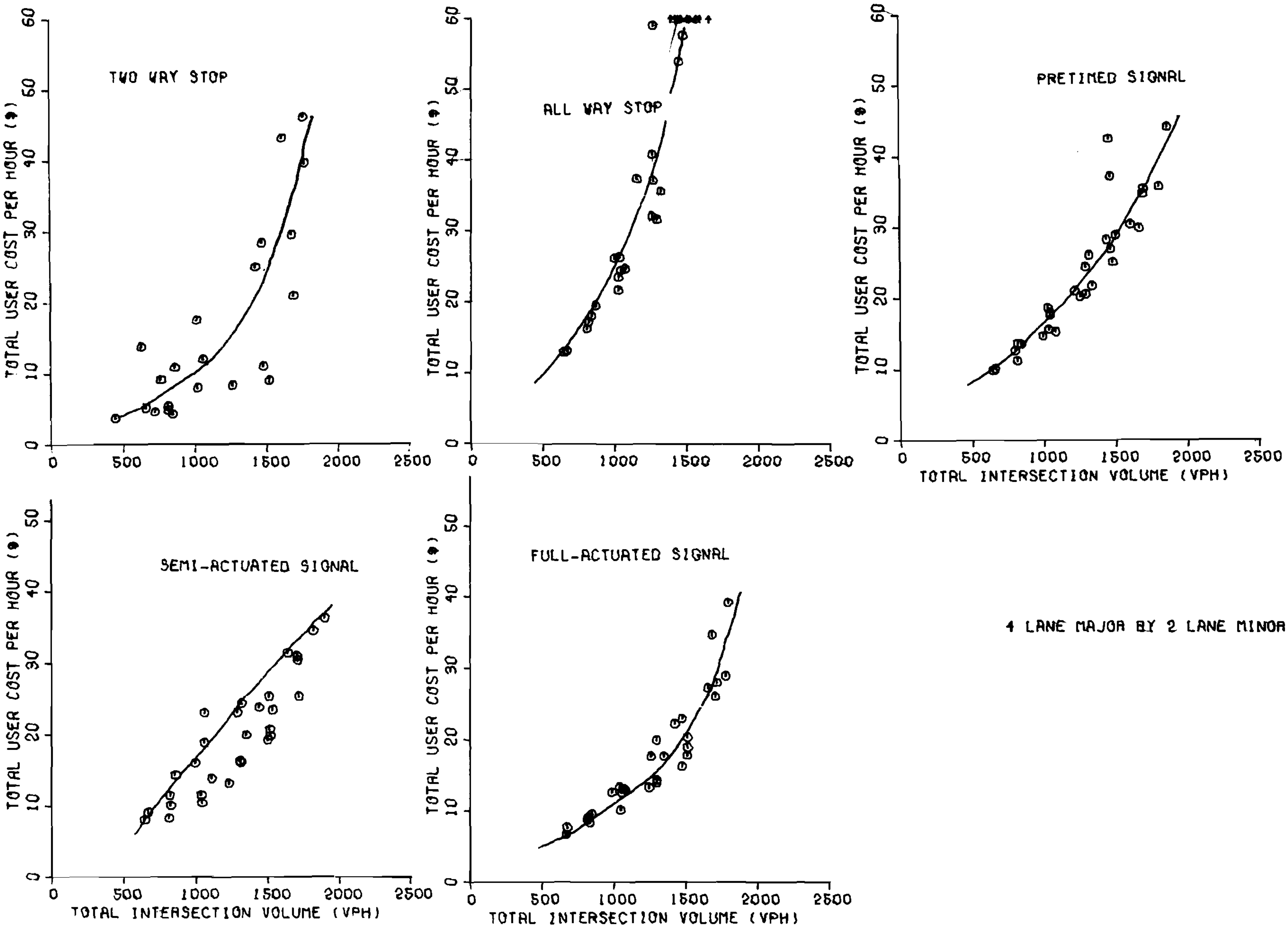


2 LANE MAJOR BY 2 LANE MINOR

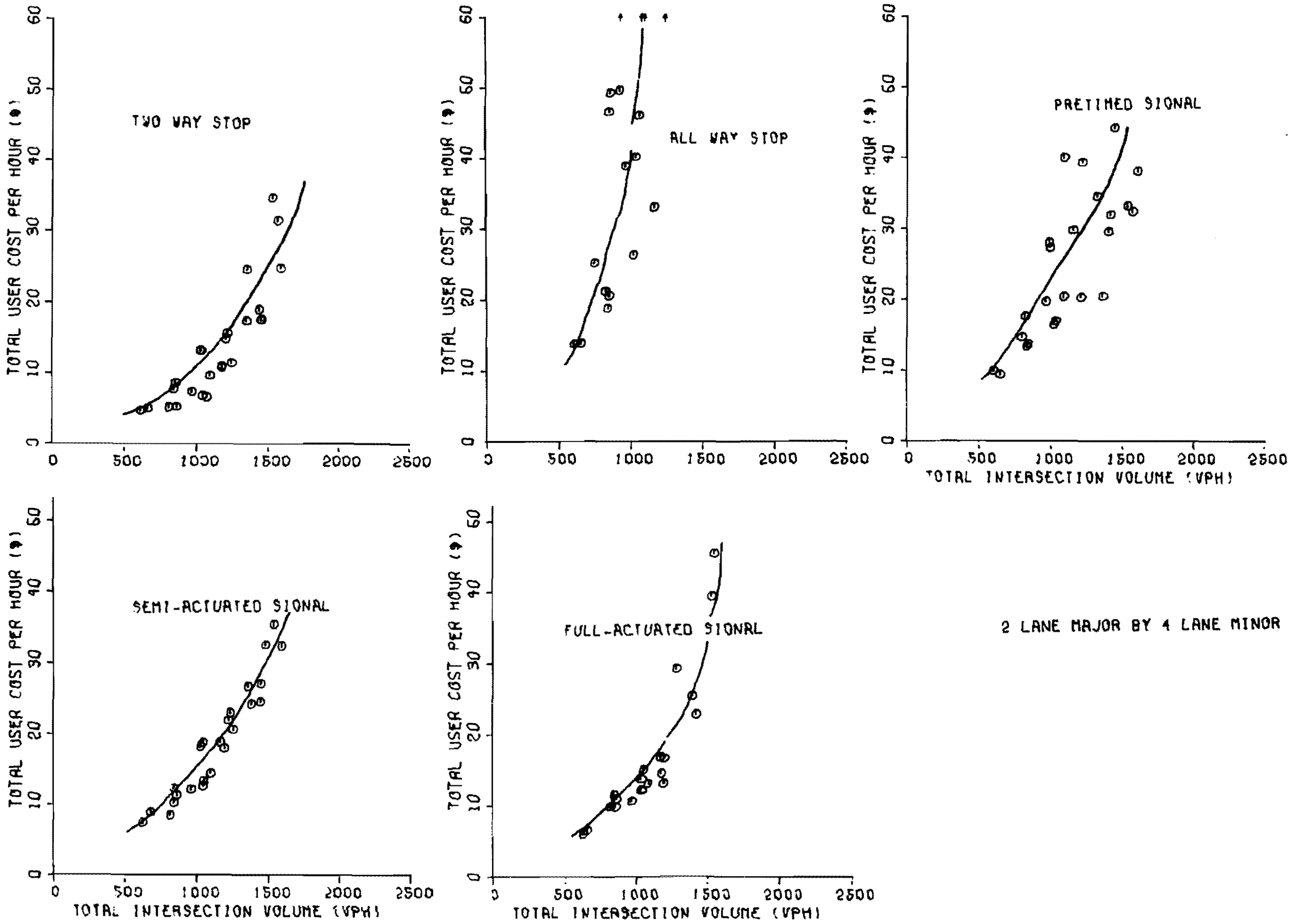

TWO WAY STOP
ALL WAY STOP
PRETIMED SIGNAL
SEMI-ACTUATED SIGNAL
FULL-ACTUATED SIGNAL
TOTAL USER COST PER HOUR ($)
APPROACH VOLUME (VPH)
0
200
400
600
800
1000
0
4
8
12
16
20
24
4 LANE MAJOR BY 2 LANE MINOR
(x : MAIN STREET)
(⊙ : MINOR STREET)


TWO WAY STOP
ALL WAY STOP
PRETIMED SIGNAL
SEMI-ACTUATED SIGNAL
FULL-ACTUATED SIGNAL
TOTAL USER COST PER HOUR ($)
APPROACH VOLUME (VPH)
0
4
8
12
16
20
24
0
200
400
600
800
1000
2 LANE MAJOR BY 4 LANE MINOR
[x : MAIN STREET]
[⊙ : MINOR STREET]

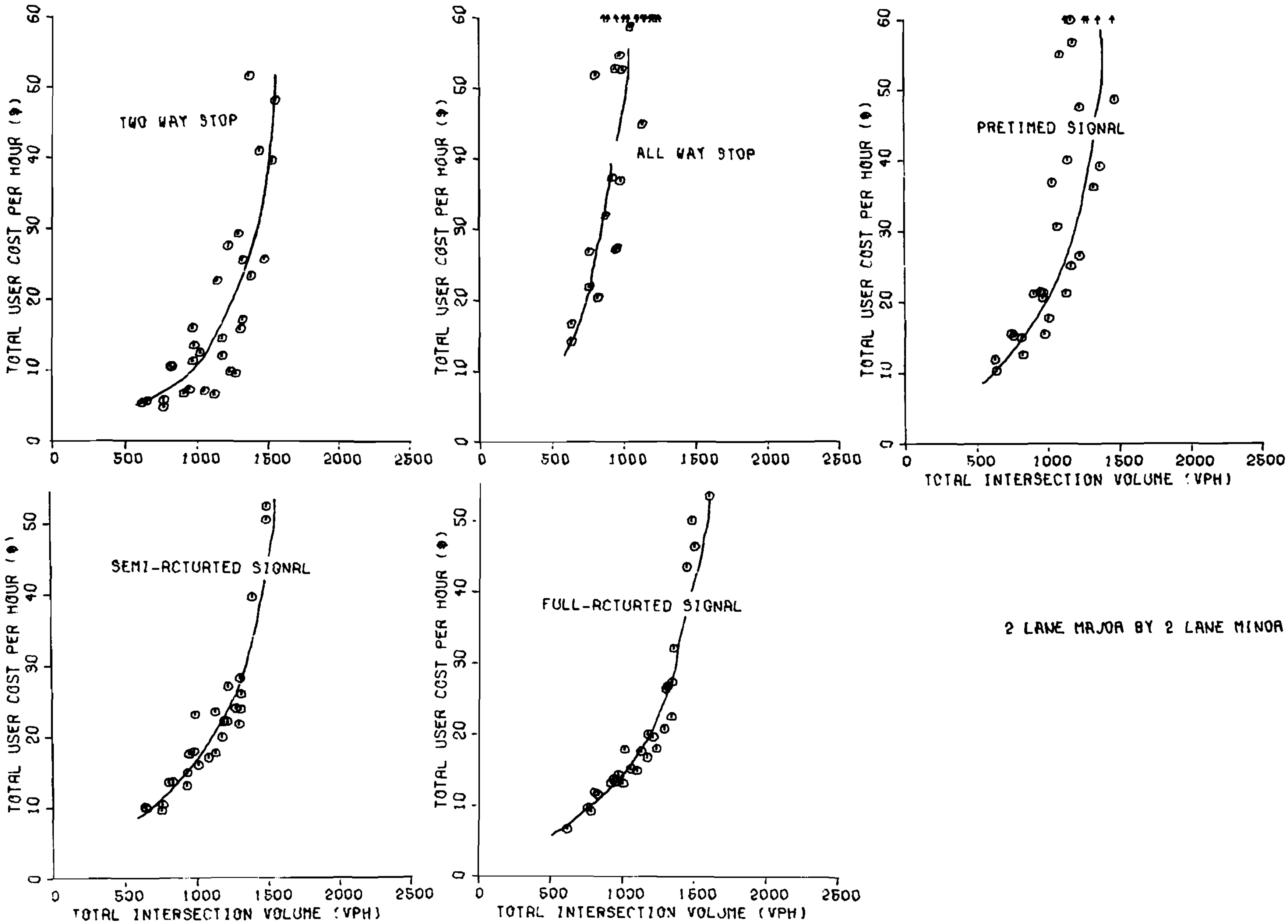

TWO WAY STOP
ALL WAY STOP
PRETIMED SIGNAL
SEMI-ACTUATED SIGNAL
FULL-ACTUATED SIGNAL
TOTAL USER COST PER HOUR ($)
APPROACH VOLUME (VPH)
0
4
8
12
16
20
24
0
200
400
600
800
1000
2 LANE MAJOR BY 2 LANE MINOR
[x : MAIN STREET]
[⊖ : MINOR STREET]



4 LANE MAJOR BY 2 LANE MINOR



2 LANE MAJOR BY 4 LANE MINOR



2 LANE MAJOR BY 2 LANE MINOR

Hour	Major Approach Volumes		Minor Approach Volumes		Major Street User Cost					Minor Street User Cost				
	EB	WB	NB	SB	2-Way Stop	4-Way Stop	Fixed-Time Signal	SA* Signal	FA** Signal	2-Way Stop	4-Way Stop	Fixed-Time Signal	SA* Signal	FA** Signal
8	325		150		1.00	7.00	5.40	3.00	3.80	3.80	3.50	2.70	3.80	2.40
		275		125	1.00	6.25	4.50	2.40	3.00	3.00	3.00	2.00	3.00	1.90
7	335		170		1.00	7.25	5.70	3.05	4.00	4.30	4.20	3.20	4.20	2.60
		283		141	1.00	6.50	4.75	2.55	3.00	3.40	3.25	3.60	3.60	2.05
6	365		173		1.00	7.95	6.25	3.40	4.50	4.35	4.25	3.25	4.30	2.65
		308		144	1.00	7.00	5.15	2.80	3.25	3.50	3.40	2.70	3.65	2.10
5	365		190		1.00	7.95	6.25	3.40	4.50	5.40	5.00	3.80	5.00	3.00
		308		151	1.00	7.00	5.15	2.80	3.25	4.00	3.90	3.20	4.00	2.40
4	367		216		1.00	8.00	6.25	3.40	4.50	6.80	6.25	4.50	5.70	3.50
		310		180	1.00	7.00	5.15	2.80	3.25	5.20	4.75	3.50	4.40	2.80
3	390		248		1.10	8.50	7.00	3.70	5.00	9.40	8.00	5.80	6.70	4.50
		330		206	1.00	7.40	5.70	3.00	3.60	6.50	6.00	4.00	5.50	3.20
2	432		278		1.20	9.50	7.75	4.25	5.40	13.50	10.30	6.80	7.80	6.10
		365		231	1.00	7.95	6.25	3.40	4.50	8.00	7.75	5.10	6.00	4.25
Peak	432		306		1.20	9.50	7.75	4.25	5.40	22.00	13.00	8.80	8.90	7.80
		365		255	1.00	7.95	6.25	3.40	4.50	10.50	9.25	5.80	6.70	4.80
Sum					16.50	122.70	95.25	51.60	65.45	113.65	95.80	67.75	83.25	56.05

Total Intersection User Cost, 8-Hour Totals	2-Way Stop	4-Way Stop	Fixed-Time Signal	SA* Signal	FA** Signal
	130.15	218.50	163.00	134.85	121.50

4 x 2 Geometry

Warrant 1 Conditions

*SA = Semi-actuated
**FA = Full-actuated

Hour	Major Approach Volumes		Minor Approach Volumes		Major Street User Cost					Minor Street User Cost				
	EB	WB	NB	SB	2-Way Stop	4-Way Stop	Fixed-Time Signal	SA* Signal	FA** Signal	2-Way Stop	4-Way Stop	Fixed-Time Signal	SA* Signal	FA** Signal
8	300		200		0.80	6.50	5.00	2.60	3.60	4.50	4.10	3.20	5.00	3.80
		200		150	0.50	4.50	3.25	1.90	2.20	3.00	3.00	2.20	3.40	3.00
7	309		226		1.00	6.70	5.10	2.80	3.75	5.00	4.95	3.50	5.30	4.20
		206		170	0.50	4.60	3.30	2.00	2.30	3.40	3.40	2.70	4.00	3.40
6	336		230		1.05	7.40	5.60	3.40	4.00	5.20	5.00	3.60	5.50	4.50
		224		172	0.50	5.00	3.50	2.20	2.50	3.50	3.50	2.75	4.20	3.50
5	336		254		1.05	7.40	5.60	3.40	4.00	5.70	5.20	4.00	6.20	4.80
		224		190	0.50	5.00	3.50	2.20	2.50	4.00	3.80	3.00	4.80	4.00
4	339		280		1.05	7.50	5.60	3.40	4.00	6.50	5.80	4.80	7.20	5.60
		226		216	0.50	5.00	3.50	2.20	2.50	4.80	4.10	3.25	5.50	4.20
3	360		330		1.10	8.10	6.10	3.60	4.25	7.95	7.10	5.60	8.10	6.70
		240		247	0.55	5.10	3.50	2.30	2.80	5.50	5.00	4.00	6.00	5.00
2	400		370		1.20	10.00	6.75	4.00	5.10	8.50	8.50	6.25	9.00	7.30
		266		277	0.60	5.50	4.00	2.50	3.00	6.20	5.80	4.70	7.00	5.50
Peak	400		408		1.20	10.00	6.75	4.00	5.10	9.90	10.00	7.00	10.00	8.20
		266		306	0.60	5.50	4.00	2.50	3.00	7.00	6.40	5.20	7.70	6.00
Sum					12.70	103.80	75.05	45.00	54.60	90.65	85.65	65.75	98.90	79.70

Total Intersection User Cost, 8-Hour Totals	2-Way Stop	4-Way Stop	Fixed-Time Signal	SA* Signal	FA** Signal
	103.35	189.45	140.80	143.90	134.30

2 x 4 Geometry

Warrant 1 Conditions

*SA = Semi-actuated
**FA = Full-actuated

Hour	Major Approach Volumes		Minor Approach Volumes		Major Street User Cost					Minor Street User Cost				
	EB	WB	NB	SB	2-Way Stop	4-Way Stop	Fixed-Time Signal	SA* Signal	FA** Signal	2-Way Stop	4-Way Stop	Fixed-Time Signal	SA* Signal	FA** Signal
8	300		150		1.00	9.40	7.00	3.50	4.80	3.80	3.50	2.60	4.00	4.10
		200		125	0.60	4.50	3.75	1.80	2.20	3.00	2.20	1.85	3.00	2.80
7	309		170		1.10	10.10	7.40	3.60	4.90	4.20	3.80	2.90	4.25	4.60
		206		144	0.60	4.75	4.00	2.00	2.25	2.50	2.80	2.40	4.00	3.60
6	336		173		1.30	11.90	8.20	4.00	5.20	4.50	4.00	3.00	4.30	4.80
		224		144	0.65	5.50	4.50	2.10	3.00	3.50	2.90	2.50	4.20	3.75
5	336		190		1.30	11.90	8.20	4.00	5.20	5.50	4.60	3.50	5.50	5.50
		224		159	0.65	5.50	4.50	2.10	3.00	4.00	3.60	3.00	4.50	4.10
4	339		216		1.30	12.10	9.00	4.10	5.40	7.00	5.15	4.00	6.10	6.80
		226		180	0.65	5.50	4.60	2.15	3.00	5.00	4.20	3.60	5.20	5.10
3	360		248		1.50	18.40	9.50	4.80	5.80	9.50	6.10	5.20	7.10	7.80
		240		206	0.70	6.10	5.00	2.50	3.10	6.00	5.00	4.10	5.80	6.00
2	400		278		1.80	30.00	11.00	5.70	6.20	13.50	8.50	6.25	8.20	10.10
		266		231	0.80	6.80	5.70	2.90	3.50	8.00	6.00	5.00	6.40	7.10
Peak	400		306		1.80	30.00	10.00	5.70	6.20	20.00	10.00	7.20	10.00	12.50
		266		255	0.80	6.80	5.70	2.90	3.50	9.60	6.80	5.60	7.20	8.50
Sum					16.55	179.25	109.05	53.85	67.35	110.60	79.15	62.70	89.75	97.15

Total Intersection User Cost, 8-Hour Totals	2-Way Stop	4-Way Stop	Fixed-Time Signal	SA* Signal	FA** Signal
	127.15	258.40	171.75	143.60	164.50

2 x 2 Geometry

Warrant 1 Conditions

*SA = Semi-actuated
**FA = Full-actuated

Hour	Major Approach Volumes		Minor Approach Volumes		Major Street User Cost					Minor Street User Cost				
	EB	WB	NB	SB	2-Way Stop	4-Way Stop	Fixed-Time Signal	SA* Signal	FA** Signal	2-Way Stop	4-Way Stop	Fixed-Time Signal	SA* Signal	FA** Signal
8	500		75		1.40	12.00	9.00	5.20	6.20	1.50	1.50	1.00	1.50	1.10
		400		75	1.00	8.90	7.10	3.60	4.90	1.50	1.50	1.00	1.50	1.10
7	515		85		1.45	12.50	9.20	5.50	6.50	1.60	1.80	1.00	1.80	1.20
		412		85	1.10	9.20	7.50	4.00	5.20	1.60	1.80	1.00	1.80	1.20
6	560		86		1.60	13.80	10.50	5.80	7.00	1.60	1.80	1.00	1.80	1.20
		448		86	1.20	10.40	8.00	4.25	5.40	1.60	1.80	1.00	1.80	1.20
5	560		95		1.60	13.80	10.50	5.80	7.00	2.00	2.00	1.05	2.20	1.50
		448		95	1.20	10.40	8.00	4.25	5.40	2.00	2.00	1.05	2.20	1.50
4	565		108		1.60	13.90	10.65	5.90	7.10	2.40	2.20	1.20	2.40	1.70
		452		108	1.25	10.60	8.05	4.40	5.50	2.40	2.20	1.20	2.40	1.70
3	600		124		1.70	15.40	11.20	6.70	7.80	2.70	2.40	2.00	2.80	2.10
		480		124	1.30	11.10	9.00	4.80	5.80	2.70	2.40	2.00	2.80	2.10
2	665		139		1.85	18.80	12.90	7.60	8.40	3.00	2.60	2.20	3.50	2.20
		532		139	1.50	13.25	10.00	5.80	6.60	3.00	2.60	2.20	3.50	2.20
Peak	665		153		1.85	18.80	12.90	7.60	8.40	3.60	2.90	2.60	3.60	2.50
		532		153	1.50	13.25	10.00	5.80	6.60	3.60	2.90	2.60	3.60	2.50
Sum					23.10	206.10	154.50	87.00	103.80	36.80	34.40	24.10	39.20	27.00

Total Intersection User Cost, 8-Hour Totals	2-Way Stop	4-Way Stop	Fixed-Time Signal	SA* Signal	FA** Signal
	59.90	240.50	178.60	126.20	130.80

4 x 2 Geometry

Warrant 2 Conditions

*SA = Semi-actuated
**FA = Full-actuated

Hour	Major Approach Volumes		Minor Approach Volumes		Major Street User Cost					Minor Street User Cost				
	EB	WB	NB	SB	2-Way Stop	4-Way Stop	Fixed-Time Signal	SA* Signal	FA** Signal	2-Way Stop	4-Way Stop	Fixed-Time Signal	SA* Signal	FA** Signal
8	400		100		1.10	30.00$^{\Omega}$	12.00	4.40	5.10	1.80	2.00	1.30	2.10	1.50
		350		75	1.00	13.00	10.10	3.60	4.40	1.30	1.50	1.05	1.50	1.10
7	412		113		1.15	30.00	12.50	4.60	5.20	2.10	2.10	1.40	2.30	1.60
		360		85	1.05	14.00	10.40	3.80	4.50	1.55	1.80	1.15	1.80	1.30
6	448		115		1.25	30.00	13.80	5.00	5.60	2.15	2.15	1.45	2.35	1.70
		392		86	1.10	25.00	11.50	4.30	5.00	1.55	1.80	1.20	1.85	1.35
5	448		127		1.25	30.00	13.80	5.00	5.60	2.40	2.50	1.60	2.70	2.05
		392		95	1.10	25.00	11.50	4.30	5.00	1.60	1.95	1.25	2.00	1.40
4	452		144		1.30	30.00	14.00	5.10	5.65	2.90	2.80	1.90	3.30	2.80
		396		108	1.10	30.00	11.70	3.40	5.10	2.00	2.10	1.35	2.20	1.55
3	480		165		1.40	30.00	16.00	5.60	6.00	3.25	3.10	2.20	4.00	3.10
		420		124	1.15	30.00	13.10	4.80	5.20	2.30	2.50	1.55	2.65	2.00
2	532		185		1.60	30.00	21.50	6.70	6.70	3.90	3.90	3.10	4.60	3.60
		465		139	1.30	30.00	15.00	5.20	5.80	2.70	2.75	1.75	3.10	2.60
Peak	532		204		1.60	30.00	21.50	6.70	6.70	4.30	4.20	3.25	5.00	4.00
		465		153	1.30	30.00	15.00	5.20	5.80	3.00	2.95	2.05	3.50	2.95
Sum					19.75	437.00	223.40	78.70	87.35	38.80	40.10	27.55	44.95	34.60

Total Intersection User Cost, 8-Hour Totals	2-Way Stop	4-Way Stop	Fixed-Time Signal	SA* Signal	FA** Signal
	58.55	477.10	250.95	123.65	121.95

2 x 4 Geometry

Warrant 2 Conditions

*SA = Semi-actuated
**FA = Full-actuated
Ω = Estimated

Hour	Major Approach Volumes		Minor Approach Volumes		Major Street User Cost					Minor Street User Cost				
	EB	WB	NB	SB	2-Way Stop	4-Way Stop	Fixed-Time Signal	SA* Signal	FA** Signal	2-Way Stop	4-Way Stop	Fixed-Time Signal	SA* Signal	FA** Signal
8	400		75		1.50	30.00$^{\Omega}$	12.00	5.30	6.60	1.30	1.50	0.80	1.20	1.50
		350		75	1.20	18.00	9.00	4.40	5.40	1.30	1.50	0.80	1.20	1.50
7	412		85		1.60	30.00	12.10	5.50	7.00	1.50	1.70	1.00	1.60	1.70
		360		85	1.30	24.00	1.30	4.50	5.50	1.50	1.70	1.00	1.50	1.70
6	448		86		1.85	30.00	14.00	6.00	7.50	1.50	1.70	1.00	1.50	1.90
		392		86	1.45	30.00	11.20	5.10	6.50	1.50	1.70	1.00	1.50	1.90
5	448		95		1.85	30.00	14.00	6.00	7.50	1.80	1.90	1.20	1.90	2.00
		392		95	1.45	30.00	11.20	5.10	6.50	1.80	1.90	1.20	1.90	2.00
4	452		108		1.90	30.00	14.20	6.20	7.70	2.10	2.10	1.50	2.10	2.10
		396		108	1.50	30.00	11.25	5.15	6.60	2.10	2.10	1.50	2.10	2.10
3	480		124		2.05	30.00	16.50	7.20	8.40	2.50	2.60	1.90	2.60	2.70
		420		124	1.65	30.00	12.40	5.50	7.00	2.50	2.60	1.90	2.60	2.70
2	532		139		2.05	30.00	20.70	8.20	9.20	3.00	2.80	2.40	2.75	3.10
		465		139	1.95	30.00	15.70	6.60	8.00	3.00	2.80	2.40	2.75	3.10
Peak	532		153		1.95	30.00	20.70	8.20	9.20	3.50	3.10	3.00	3.50	4.00
		465		153	1.95	30.00	15.70	6.60	8.00	3.50	3.10	3.00	3.50	4.00
Sum					25.70	462.00	219.95	95.55	116.50	34.40	34.80	25.60	34.10	38.00

Total Intersection User Cost, 8-Hour Totals	2-Way Stop	4-Way Stop	Fixed-Time Signal	SA* Signal	FA** Signal
	60.10	496.80	245.55	129.65	154.50

2 x 2 Geometry

Warrant 2 Conditions

*SA = Semi-actuated
**FA = Full-actuated
Ω = Estimated