Microscopic Traffic Simulation Package for Isolated Intersections

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The Center for Highway Research at the University of Texas at Austin has developed a new microscopic traffic simulation package, called the traffic experimental and analytical simulation (TEXAS) model, that can be used to evaluate existing or proposed intersection designs and to assess the effects on traffic operations of changes in roadway geometry, driver and vehicle characteristics, flow conditions, intersection control, lane control, and signal timing plans. A geometry processor calculates vehicle paths on the approaches and in the intersection, identifies points of conflict between intersection paths, and determines minimum available sight distance along each inbound approach. A driver-vehicle processor generates individual driver-vehicle units and describes their characteristics. An auxiliary headway distribution analysis processor helps select an appropriate headway distribution. A simulation processor simulates the movement of each driver-vehicle unit through the system and gathers performance statistics. Linear acceleration and deceleration models and a noninteger, microscopic, generalized car-following equation are used. Traffic signal simulators are included for pretimed, semi-actuated, and fully actuated controls. Other intersection control options include no control and yield, less-than-all-way stop, and all-way stop signs. New simulation techniques include lane change decision and geometry, sight distance restriction checking, intersection conflict checking, and storage management and logic processing methods. A new field device for recording validation data and for determining suitable model input is described. Input was designed to be user oriented and minimal; output is concise and functional. Documentation has been developed for both users and programmers.

Satisfactory solutions to traffic control problems at intersections involve evaluating capacity, efficiency, safety, environmental impact, and cost and, therefore, always require a detailed analysis of the expected individual driver-vehicle response to the complex geometry, traffic, and control conditions. Inadequate predicting and tracing methods have plagued transportation engineers through the years and have limited them to macroscopic estimates of traffic stream flow characteristics for their analyses and designs.

Advances in digital computer technology during the past decade, however, have allowed complex simulations that are quite sophisticated. Several traffic simulation programs have been developed, but none of these has been designed specifically to handle the single, multileg, multilane, mixed-traffic intersection operating either without control or with a conventional traffic control.

In 1971, development of such a program was undertaken as part of the Cooperative Research Program between the Texas State Department of Highways and Public Transportation and the Center for Highway Research at the University of Texas at Austin. The scope of the study was purposely restricted to simulation of traffic at a single intersection, since other models were being designed to handle primarily multi-intersection, signalized networks. Emphasis was placed on making the simulation package user oriented and on minimizing computational requirements.

The result of this research is a microscopic traffic simulation package called the traffic experimental and analytical simulation (TEXAS) model for intersection traffic (1, 2, 3, 4). In this model, each individually characterized driver-vehicle unit is examined separately. At selected time intervals the computer program provides the simulated driver with information such as desired speed, destination, current position, velocity, acceleration, relative position and velocity of adjacent vehicles in the system, critical distances to be maintained, sight restrictions, and location and status of traffic control devices. The simulated driver may maintain speed, accelerate, decelerate, or maneuver to change lanes. Response is a function of driver and vehicle characteristics, roadway geometry, traffic control, and actions of other driver-vehicle units in the system. The highest priority logical response of the driver-vehicle unit is determined on the premise that the driver wants to maintain a desired speed but that he or she will obey traffic laws and maintain safety and comfort.

Structured programing techniques were used in developing the simulation model and storage requirements kept to a minimum. FORTRAN IV was used on both CDC and IBM computers. The overall structure of the model was arranged in three separate processors for computational efficiency.

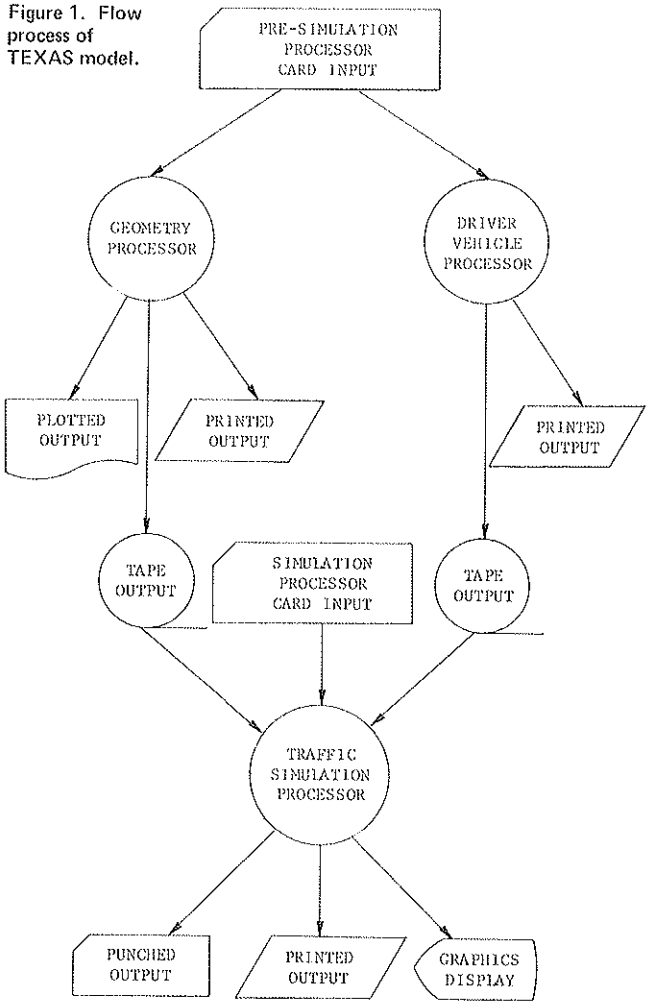
ORGANIZATION OF THE TEXAS MODEL

An essential function of the simulation process is the definition of the geometry of the intersection. A special geometry processor (GEOPRO) was developed to calculate and store all geometric details that would be held constant for each simulation run. Likewise, a driver-vehicle processor (DVPRO) was developed to characterize each driver-vehicle unit in the simulated traffic stream. Repetitious computations that are required for simulating the movement of each driver-vehicle unit through the intersection in response to the geometry, traffic, and control conditions were incorporated into a simulation processor called SIMPRO. The interrelation among these three processors is shown in Figure 1. Documentation for the model includes a programmer's guide, a user's manual, and numerous comment statements in each processor (1, 2, 3).

Geometry Processor

GEOPRO 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 each inbound approach (5). This information, first processed so that all need for Cartesian coordinate information within the simulation processor is eliminated, is then written onto a tape for subsequent use by SIMPRO. The generalized input is the GEOPRO title, and information for the approach, the lane, the arc (for plotting), the line (for plotting), the sight distance restriction, and the GEOPRO options, which include the path "type" option, the plot option, the maximum radius for intersection paths, the definitions for straight and U-turn movements, and the minimum distance between two intersection paths for a

Figure 1. Flow process of TEXAS model.



conflict. Most of the information required will normally be available from a plan view diagram of the intersection.

GEOPRO uses straight-line segments and arcs of circles to describe paths that vehicles will follow in the intersection. Algebraic equations for the intersection of two lines, the intersection of an arc and a line, and the intersection of two arcs are used for calculating points of conflict between paths. Safe-side friction factors are used to compute maximum vehicle speed for negotiating an intersection path. The minimum available sight distance between inbound approaches is calculated for each 7.6-m (25-ft) increment along an inbound approach. Printed output from GEOPRO includes an echo print of the input, a listing of minimum available sight distances between inbound approaches, a listing of the intersection paths, a listing of conflicts between the intersection paths, and certain input or execution errors. Plot output is optional but may include a plot of the full length of all approaches and sight distance restriction points, a plot of an enlargement of the intersection area, and a plot showing all generated intersection paths. Tape output includes the title for GEOPRO and all geometry information needed as input for the SIMPRO. The proper functioning of GEOPRO was verified by analyzing debug prints and plots from various test data sets.

GEOPRO requires 26 900 words of storage on CDC 6600 computers and 176 000 bytes of storage on IBM 370-155 computers. Geometry computations in the central processor for an average intersection take 6.3 s on CDC computers and 9.2 s on IBM computers.

Driver-Vehicle Processor

DVPRO describes the characteristics of several driver and vehicle classes, generates individual driver-vehicle units, and orders these units sequentially by queue-in time. This information is stored on tape for later use in SIMPRO. The generalized input to DVPRO includes the DVPRO title; the approach information; the lane information; the driver-vehicle processor options, which include the number of minutes for generating traffic, the minimum time between two vehicles in the same lane, and a variety of options that would allow for an override of the standard program-supplied driver-vehicle mix; and special driver-vehicle units. Such information will usually be available from experience with similar intersections or from routine traffic studies. A common input card deck for DVPRO and GEOPRO is used because much of the information is the same.

In DVPRO, headways of vehicles that arrive on each inbound approach are generated as random variables of one of the following distributions: uniform, log normal, negative exponential, shifted negative exponential, gamma, Erlang, or constant. Mean headway for traffic on each inbound approach is calculated from the specified volume for that approach, and only one additional parameter, which indicates randomness, needs to be specified to describe these distributions. Driver and vehicle class, desired outbound approach, and inbound lane number are generated as random variables of empirical distributions (percentages specified by the user). Desired speed is generated as a random variable of the normal distribution; the user prescribes the mean and the 85th percentile speed.

Printed output includes an echo print of the input, statistics of generation, and certain input or execution errors. Tape output includes the DVPRO title and all information necessary for SIMPRO. DVPRO requires 14 500 words of storage and typically 2 s of central processor time for 12 min of traffic on CDC computers and 95 000 bytes of storage and 3 s of central processor time on IBM computers.

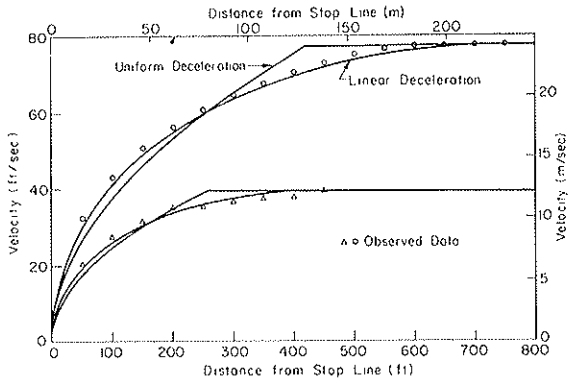
The proper performance of DVPRO was verified by analyzing debug prints of sample problems and by using a special distribution analysis processor called DISPRO. DISPRO is an ancillary processor that fits selected mathematical distributions to empirical headway data. Chi square is then calculated as a goodness of fit indicator for each distribution, and the maximum cumulative difference is found for a Kolmogorov-Smirnov one-sample test. As an aid to the user, a histogram of the input headway data and of each distribution fitted is plotted.

Simulation Processor

Input Requirements

The purpose of SIMPRO is to process each driver-vehicle unit through the intersection system and to gather and print performance statistics about the simulation. The input requirements for SIMPRO are the output tape produced by GEOPRO, the output tape produced by DVPRO, and card input to SIMPRO. The card input consists of SIMPRO title and options, which include start-up and simulation time; time-step increment for simulation; speed for delay below a set speed; maximum clear distance for being in a queue; lambda, mu, and alpha values for the generalized vehicle-following equation; type of intersection control; desired summary statistics; time for lead and lag zones for intersection

Figure 2. Velocity versus distance during normal deceleration to a stop.



conflict checking; and lane control for each lane. For a signalized intersection, additional card input is necessary. The signal indication information for each inbound lane consists of input that models the cam stack found in most signal controllers plus the timing scheme for displaying each interval. If the intersection is actuated, supplementary information about detector type and location is required. Highly sophisticated, multiphase controllers, except volume-density types and minicomputers, are modeled in detail, and all required input information can be obtained from conventional sequence patterns and interval timing plans that are familiar to transportation engineers.

Overview

SIMPRO uses a fixed-time increment in the ½ to 1 s range. It basically has three types of links on which to simulate driver-vehicle units: outbound approaches where there is no control mechanism at the end, intersection paths, and inbound approaches where there may be a control mechanism that regulates entry into the intersection. SIMPRO processes driver-vehicle units on outbound approaches, then on intersection paths, and then on inbound approaches; then new driver-vehicle units are added to the system; and finally signal status is processed.

Validation of SIMPRO proceeded in two stages: validation of its specific portions and validation of its performance statistics.

Acceleration

For the model to replicate real-world phenomena as accurately as possible, a thorough investigation of acceleration and deceleration models was undertaken. The uniform acceleration model frequently used does not match observed behavior accurately on a microscopic scale. A linear acceleration model that hypothesizes use of maximum acceleration when vehicle velocity was zero, zero acceleration at desired velocity, and a linear variation of acceleration over time was adopted. Comparisons of this model with observed data (6, Figure 2.10, p. 27) indicated excellent agreement. This model also compared favorably with the nonuniform acceleration theory (7, p. 9) used in describing the maximum available acceleration for the vehicle.

The parameter that is determined by driver desire in effecting the position, velocity, and acceleration of the vehicle is acceleration slope (jerk). Dramatic changes in acceleration in a short period of time are restricted in the model by limiting acceleration slope range.

In validating the acceleration models, position, velocity, and acceleration versus time plots were produced by SIMPRO and checked to ensure that the vehicles responded in a reasonable manner under varying conditions. Studies by Beakey (8) led to the development of the relationship between maximum initial acceleration and desired speed that is used in SIMPRO (9, p. 10).

Deceleration

The investigation of deceleration models revealed that the uniform deceleration model did not closely approximate actual vehicle behavior. We chose a linear deceleration model in which the vehicle has an initial deceleration of zero and reaches maximum deceleration at the instant the vehicle stops and in which deceleration rate varies linearly over time. Comparisons of this model with real-world data (6, Figure 2.14, p. 30) indicate that the model very accurately represents vehicles decelerating to a stop (Figure 2). Again, the parameter that affects the position, velocity, and deceleration of the vehicle is deceleration slope (jerk).

Validation of the deceleration models was the same as that for the acceleration models.

Car-Following

Several car-following techniques were investigated, but the noninteger, microscopic, generalized car-following equation (10) was selected because of its superiority and flexibility. A value of deceleration was computed from the equation, and then we chose a deceleration slope that brought the vehicle to the computed value of deceleration in one time increment. Studies by May (11) indicated acceptable ranges for lambda and mu in the car-following equation. Values used in the TEXAS model may range from lambda of 2.3 to 4.0 and mu of 0.6 to 1.0.

In validating the car-following model, position, velocity, and acceleration versus time plots were produced and checked by SIMPRO.

Acceleration and Deceleration Logic

To determine a unique response for each driver (accelerating to desired speed, accelerating to lead vehicle speed, following the vehicle ahead, remaining stopped, checking whether deceleration to a stop is necessary, or continuing deceleration to a stop), a logical binary network for acceleration and deceleration was developed and used in the model. The model maintains current values for all independent variables in the network and executes a special logic routine to determine the appropriate decision for the conditions.

Signalization

The signal indications displayed to traffic on each inbound lane are determined from information provided on card input and from the dynamic response of a simulated controller. For a pretimed controller, the specified sequence of indications is implemented, and the duration of each interval is referenced to a simulated real-time clock. In representing a traffic-actuated controller, all time intervals, including those affected by detector actuation, are simulated. During any particular green indication, the controller may extend the green, "max out," or "gap out" according to time limits, detector actuations, and presence or absence of demand for another phase. Appropriate amber and all-red clearance intervals are provided.

When the signal indication changes for the driver, the appropriate response (enter the intersection and do not check conflicts, enter the intersection and check conflicts, go on amber, stop on amber, or stop for red) is determined. The go or stop-on-amber decision is based upon whether a driver-vehicle unit can stop at the stop line without exceeding a maximum level of deceleration.

Validation was based on testing many cases of amber-go and amber-stop decisions for reasonableness and consistency. Delay to the first vehicle in the queue and "march-out" headways were compared with observed values (12). In this comparison, particular attention was given to the location of the screen line as suggested by Berry (13).

Intersection Logic

To define driver response to intersection control, a logical binary network was developed and used in the model. The model maintains correct values for all independent variables and, after executing a logic routine, sets dependent variables to proper values. This determines the conditions under which a driver-vehicle unit may enter the intersection.

Lane Change

The TEXAS model distinguishes between two types of lane changes: the forced lane change (the currently occupied lane does not provide a path to the desired outbound approach) and the optional lane change (less delay can be expected by changing to an adjacent lane that also connects to the desired outbound approach). The decision to change lanes is controlled by the availability of an acceptable gap. A cosine curve is used to represent the path followed during the lane-change maneuver.

Time-lapse photography served as the basis for the development of equations for acceptable lead and lag gaps for a lane-change maneuver (14). The time required to complete a simulated lane-change maneuver is approximately 3 to 4 s for any reasonable speed. Numerous test cases were conducted to ensure that lane changes, both forced and optional, were made in a reasonable and safe manner under various conditions.

Sight Distance Restriction

GEOPRO locates all sight obstructions from information included as input and calculates the distance that is visible along other inbound approaches for each 7.6-m (25-ft) segment of an inbound approach. SIMPRO then stores this information as a series of data arrays. The simulated driver utilizes the information in evaluating the effects of sight restrictions to ensure that the impending entry into the intersection will be legal and safe. He or she controls the velocity of the vehicle in such a way as to avoid a potential collision with a hypothetical vehicle that may be hidden from view by the obstruction.

Intersection Conflicts

In checking conflicts, the simulated driver forecasts time of arrival at points of potential conflict and compares this with the projected arrival time of other vehicles in the intersection and other vehicles already committed to entering the intersection. The decision to enter the intersection is then based on whether the driver's vehicle can pass safely through the point of conflict in front of or behind other vehicles that have the right-of-way. Conflict computations are executed only for those vehicles that may be required to yield to other approaching vehicles.

Storage Management and Logic Processing

SIMPRO uses a special storage management and logic processing program called COLEASE, which provides a mechanism for storing specified variables in a format that maximizes computer bit usage by disregarding normal word boundaries. COLEASE also allows efficient processing of logical binary networks (15) and reduces the main storage requirements on CDC computers to approximately one-seventh of that normally required.

Output

Output from SIMPRO consists of title from the GEOPRO tape, title from the DVPRO tape, title from the card input to SIMPRO, echo print of all card input to SIMPRO, information about each collision (if collisions occur), listing of driver-vehicle units eliminated (if any) from the simulation because of full entry lane, summary statistics, and certain input or execution errors. Summary statistics include total delay; queue delay; stopped delay; delay below a set speed; total and average vehicle travel distance; total and average travel time; number of vehicles processed and equivalent hourly volume; average desired speed, time-mean speed, and space-mean speed; average maximum uniform acceleration and deceleration; average and maximum number of vehicles in the queue for each lane; average ratio of entry speed to desired speed; and actuated signal performance indicators. Total delay is defined as the actual travel time through the system minus hypothetical desired travel time. Queue delay is that spent in a queue waiting to enter the intersection; it includes move-up time. Stopped delay is that spent stopped in queue waiting to enter the intersection; it does not include move-up time. Delay below a set speed is the amount of time traveled at a velocity less than or equal to that speed anywhere in the system.

Validation

Performance of the simulation processor was evaluated through independent testing of selected subprograms, analysis of position, velocity, and acceleration-versus-time plots, and review of interactive graphics displays of the movement of individual vehicles through the system. Figure 3 illustrates the position and velocity-versus-time plot for a test case in which the first vehicle entered the system at 9 m/s (30 ft/s) and 7 s later the second vehicle entered at 15 m/s (50 ft/s). After about 12 s the second vehicle overtook the first and decelerated until the speeds matched. The first vehicle later decelerated until the speeds matched. The first vehicle later decelerated to a stop at the intersection, and the second vehicle stopped behind the first. After the first vehicle entered the intersection, the second vehicle advanced to the stop line and, after checking potential conflicts, entered the intersection. The second vehicle again caught up with the first and trailed at a safe distance. The smooth trajectory of each vehicle indicates that all components of the model functioned properly for this test case.

SIMPRO was validated by comparing various performance statistics from the model with data from field observations. The primary basis for comparison was delay resulting from different traffic demands, types of control, and intersection configurations. Extensive in-

Figure 3. Position and velocity versus time trajectories for two vehicles.

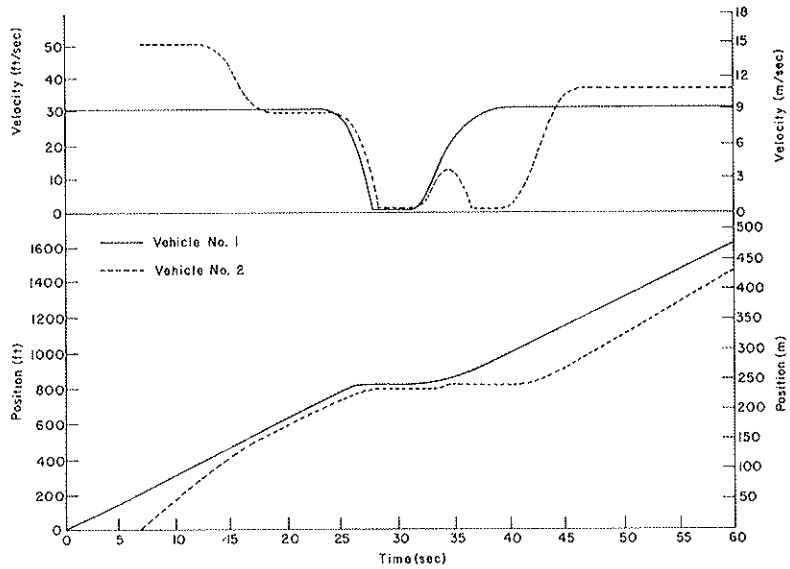
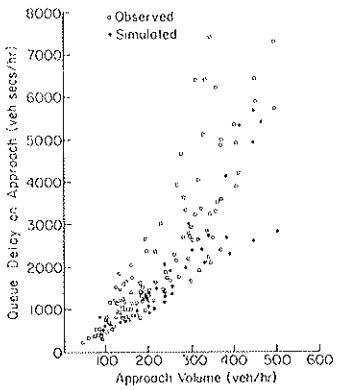


Figure 4. Delays at five intersections.



tersection delay and volume data were available from a previous research study (16), and special additional studies were conducted for validation of the TEXAS model. The earlier data were entered into an electromechanical recording device.

A new recording device was developed and used for the more recent field studies. This was superior to the older one in the following features: portability, independent dc power supply, solid-state electronic component reliability, accurate time reference synchronized for several units, display of the current counter reading to the observer, use of an inexpensive voice-grade cassette tape recorder for storing digital data in analog form, and economical construction and maintenance. Each second, the recording device interrogates two counters (which are kept current by an observer using an increment, decrement, and zero switch) and writes digital values, current time, and recording device identification number onto a cassette tape.

The field observation technique that was used to measure queue delay at nonsignalized intersections called for an observer to increment a counter each time a vehicle joined the queue waiting to enter the intersection; this counter was decremented each time a vehicle crossed the stop line and entered the intersection. Thus the current number of vehicles in the observed queue was indicated by the counters. Volume information was obtained by having another observer increment a counter each time a vehicle entered the intersection. At signalized intersections the observer used a similar technique to keep a current indication of the number of vehicles that were actually stopped while waiting in a queue to enter the intersection.

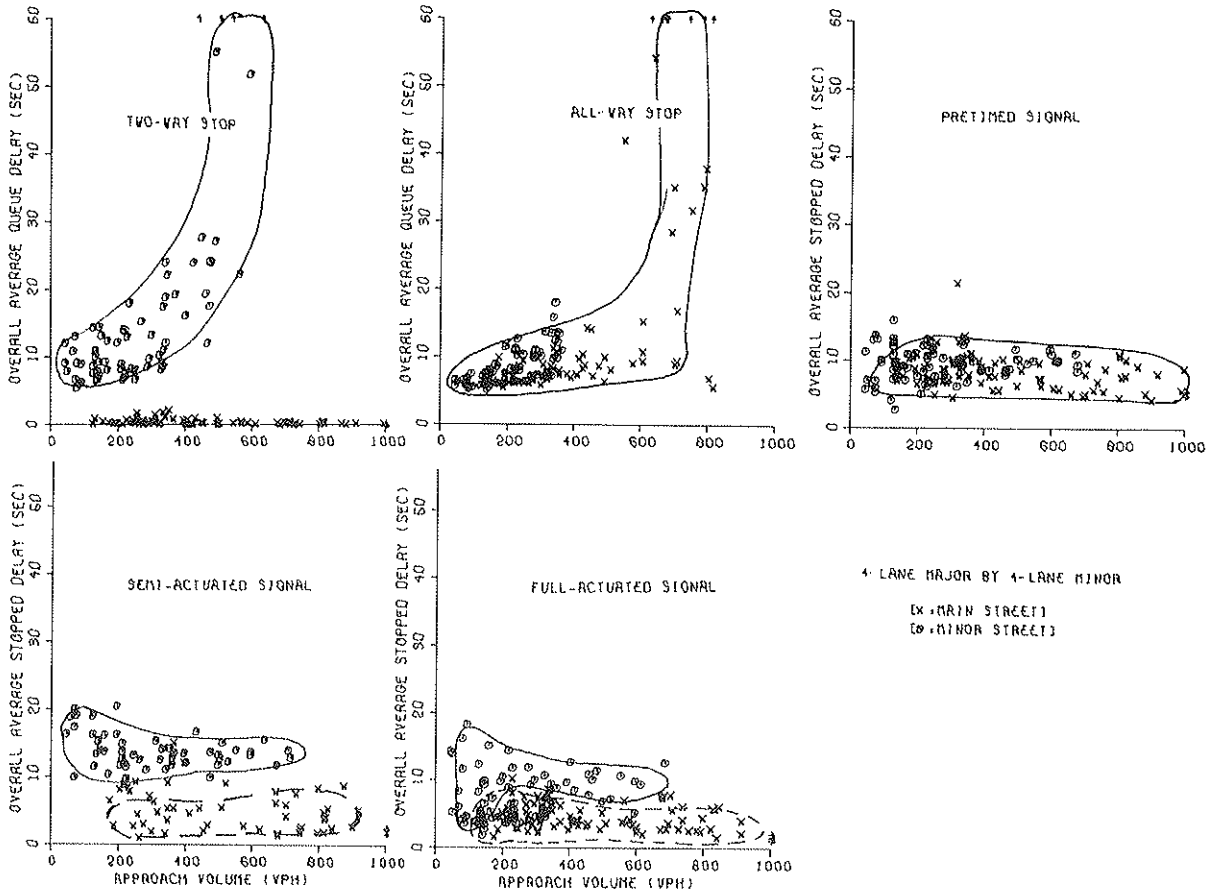
Data from the cassette tapes were retrieved in two steps: (a) the data stored in analog form on as many as six tapes were simultaneously converted to digital form by an analog-to-digital conversion processor (ADPRO) on a Hewlett Packard HP2115A computer system; and (b) the appropriate statistics were computed from the digital data by using a special delay, volume, and headway processor (DVHPRO).

Initial comparisons of simulated delays with observed delays indicated the need for adjusting certain components of the model in order to obtain satisfactory agreement over a wide range of traffic volumes. Modifications were made in the maximum velocity at which a vehicle first enters the queue and begins experiencing queue delay and stopped delay or both, the value of the time zones that the driver considers safe when checking intersection conflicts, the hesitation time for vehicles entering unsignalized intersections, the hesitation time for the first vehicle in a queue entering the intersection when the signal turns green, and the parameters for the generalized car-following equation (lambda, mu, and alpha). The resulting agreement between the observed and the simulated delay values, as shown in Figure 4, is one example that demonstrates the validity of the TEXAS model.

Computer Time and Storage Requirements

The computer time requirements for SIMPRO are difficult to reduce to a single value. As an indication of the efficiency of the model, a simulated 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 length, the time-step increment, and the total number of vehicles processed. For signalized intersections, 180-m (600-ft) lanes, and a time step increment of 1 s, the lower limit of efficiency (worst) is in the general range from 30 at a total equivalent hourly volume of 1000 vehicles/h to 8 at a volume of 2000 vehicles/h. The upper limit of efficiency (best) is 45 and 15 respectively for the same volumes. For nonsignalized intersections, 180-m (600-ft) lanes, and a time step increment of 1 s, the lower limit of efficiency (worst) is in the general range from 40 at a volume of 750 vehicles/h to 8 at a volume of

Figure 5. Simulated delays for five types of controlled intersections.



1250 vehicles/h. SIMPRO uses 32 250 words of storage on CDC computers and 210 000 bytes of storage on IBM computers.

USES OF THE TEXAS MODEL

This model may be used to study traffic behavior at an intersection operating either without control or with any conventional control. Features of the model that make it particularly suitable include accommodation of 5 driver classes and 15 vehicle classes; 6 approaches with 6 lanes/approach; 305-m (1000-ft) lane lengths; sight restrictions; uncontrolled operation; sign-controlled operation; 8-phase signal control with skip-phase, dual-left, and parent-and-minor options; 2 detector types and 5 detectors/lane; 72 signal intervals; geometrically correct lane-changing maneuvers and paths through the intersection; and left-turn or right-turn-on-red options. The effects of changes in roadway geometry, driver and vehicle characteristics, flow conditions, intersection control, lane control, and signal control options can be readily evaluated.

More than 600 runs of the TEXAS model have been made, and the results have been evaluated in relation to capacity analysis of unsignalized intersections and warrants for various types of control (4, 17, 18). Figure 5 illustrates these results for comparable values of overall average delays (total delay divided by the total number of vehicles using an approach) for an intersection with four lanes on both major and minor streets.

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Abridgment

Postoptimality Analysis Methodology for Freeway On-Ramp Control

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Postoptimality analysis is concerned with changes in an optimum decision value caused by changes in the parameters (input data) of a decision model. It is one way of approaching issues of uncertainty when using deterministic techniques such as linear programing (LP). We applied the techniques to a northbound section of the Eastshore Freeway (I-80) in the San Francisco Bay Area. The LP technique bases its calculations on point estimates rather than on a range of values. Postoptimality analysis assists in determining the importance and effects of deviations from such estimates.

The superiority of postoptimality analysis associated with LP over other mathematical programing techniques lies in its simplicity and systematic procedures. Postoptimality analysis allows us to obtain from the final (optimum) LP tableau (in addition to the optimum solution) a wealth of information on a wide range of operations in the neighborhood of the optimum.

Previous studies have focused on the potential applications of postoptimality analysis (1, 2). However, no such analysis has been attempted in recent applications of LP to freeway on-ramp control (3, 4).

It should be clear that one way to analyze postoptimality is to formulate and resolve a modified problem. This modification could, for example, be a slight change in one of the model parameters. Still, to investigate the effects of this slight change, the analyst must put this change into the model and rerun the program. Such a procedure is clearly inefficient and time consuming. Substantial economy of time and analysis is often possible if the information available in the optimum solution to the original problem is fully utilized instead. We shall demonstrate this.

THE LP CONTROL MODEL

The LP control model used here is similar to Wattleworth's original formulation and can be regarded as a resource allocation model. The resources—freeway subsection capacities—are allocated to competing input-station demands in order to maximize a certain objective function (for example, total allowable input rate) that is subject to the constraint of no congestion on the freeway and other operational constraints. The allowable flow rates at each input station are our decision variables, which are typically characterized by the upper and lower bounds imposed on them. Eldor has presented the mathematical details of the model (5, 6).

POSTOPTIMALITY ANALYSIS METHODOLOGY

The type of postoptimality analysis that can be performed on variations of a parameter depends upon its role in the optimization problem. The LP technique allows the effects of some variations to be examined quite easily.