Assessment of the Traffic Experimental and Analysis Simulation Computer Model Using Field Data

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Computer simulation techniques and their applications to traffic operations have gained popularity in recent years. The traffic experimental and analysis simulation (TEXAS) computer model is a prime example. This model was developed to be used as a tool to evaluate traffic performance at isolated intersections operating under various types of intersection control. The objective of this study was to assess the ability of the TEXAS model in simulating isolated signalized intersections. This assessment was conducted using field data. Eight intersection conditions were used for data collection. Existing field data were obtained from previous studies and supplemented with more data collection where needed. Critical 10-min time periods were chosen for the simulation runs, and the average stopped delays obtained from simulation were compared with the observed stopped delay data. Statistical tests were conducted; the results indicated that in most of the intersection conditions no significant difference was observed for through traffic. However, significant differences between field and simulated results were achieved for left-turning traffic. These findings were limited to eight intersection conditions studied in Arizona, and it suggests that the user of the model is advised to carefully assess the default variables embedded in TEXAS.

Traffic simulation models are computer programs that are designed to represent realistically the behavior of the physical system. The major advantage of using a simulation model is its ability to compare and evaluate alternate solutions of a single problem by changing the variables in the model without physically going out to the field to make the change. This analysis tool is effective in comparing different scenarios before deciding on one to implement, thus reducing costs that would otherwise be incurred if an unsuccessful scenario is implemented. Another advantage is that a simulation model can give results for variables that would otherwise be difficult to obtain from field measurements.

Painting a rosy picture about computer simulation could be deceiving. The user of computer simulation models has to be careful about how the model is being used and how much faith the user has in the results. A well-validated simulation model can be a powerful tool. Validation involves large-scale field data collection for different values of selected variables followed by using the model to create the same circumstances in the computer. The produced results are then compared against the field data to decide whether the model realistically replicates the real world. If the comparison indicated that the field data are significantly different from the simulated results, refinement of the model variables is then pursued.

This study focused on traffic operations at isolated signalized intersections. Intersections are usually the critical component of a traffic network in the urban area. One of the traffic simulation models developed for isolated intersections is the traffic experimental and analysis simulation (TEXAS) computer model.

The main goal of this research was to compare delay data collected in previous field studies with the delay predicted by the TEXAS computer model. The main purpose of this exercise was to attempt to assess the simulation model in terms of its ability to replicate the real world without changing the default values. The field data used for the assessment purpose came from three related studies. Most of the data for this effort were provided by Matthias and Upchurch (*1*). The remainder of the data were taken from two theses (*2,3*). Although some of the data are close to 5 years old and were collected for the purpose of developing left-turn signal warrants, the data collection method provided comprehensive information that could be used with high confidence to assess a traffic simulation model.

THE TEXAS SIMULATION MODEL

The TEXAS model is a microscopic simulation model. It was developed by the University of Texas at Austin for the Texas State Department of Highways and Public Transportation (*4–6*). In a microscopic model, each vehicle in the traffic stream is monitored individually. The model can be used as a tool by transportation engineers to evaluate traffic performance at isolated intersections operating under various types of intersection control.

The model is divided into three main parts, a geometry processor called GEOPRO, a driver-vehicle processor called DVPRO, and a traffic simulation processor called SIMPRO.

The geometry processor accepts data describing the physical configuration of the intersection such as the number of legs and the number of lanes and their widths. The processor calculates the geometric path of vehicles on the approaches and within the intersection, identifies points of conflict between intersection paths, and determines the minimum available sight distance along each inbound approach.

The input requirements for this processor include approach information such as the number of inbound and outbound approaches, the speed limit for each approach, the number

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of lanes for each approach, and the maximum angular deviation of through movement and U-turn movement for each approach. Lane information, such as the width of each lane, the geometry of each lane, and the turning movements generated from each inbound lane and accepted by each outbound lane, is also required.

The driver-vehicle processor stores information related to the driver characteristics and the vehicle characteristics in the traffic stream. The processor generates driver-vehicle units for use by the traffic simulation processor. Each one of these units is randomly assigned a driver class, a vehicle class, a lane, a turning movement, and a desired speed using a discrete empirical distribution. The total number of driver-vehicle units generated depends on the vehicular volume and on the simulation time. The processor then orders these units sequentially by queue-in time.

The input data required for this processor, for each intersection approach, includes the headway distribution and its parameter, the minimum headway, the hourly traffic volume, the mean and 85th percentile speeds, the turning distribution (percent of vehicles going to each outbound approach), the lane occupancy, the time for generating traffic, and the number of driver and vehicle classes (*2*). The model has seven different types of headway distributions to choose from. They are the constant, the Erlang, the gamma, the log-normal, the negative exponential, the shifted negative exponential, and the uniform distributions. The time for generating traffic is made up of the start-up time plus the simulation time. In the start-up time period, if the flow through the system has not attained a steady state condition (*3*) then the performance statistics are unreliable. After the specified start-up time, flow is assumed to have reached steady state and it is followed by the simulation time period. Another input requirement for this processor is the percent of left-turning vehicles to enter in the median lane and the percent of right-turning vehicles to enter in the curb lane.

The traffic simulation processor uses the output from the previous two processors and processes each driver-vehicle unit through the intersection system. This processor simulates the traffic behavior of each driver-vehicle unit depending on its surrounding conditions. The driver-vehicle unit is monitored second-by-second from the time it enters an inbound approach until it leaves the system from an outbound approach. The processor adjusts the movement of the driver-vehicle unit depending on various elements, such as the indication of the traffic control device, the presence of a vehicle ahead, and whether the driver-vehicle unit is in a car-following situation.

The input data requirements for a simulation run are the type of intersection control, the start-up and simulation time, the time step increment for simulation, the maximum clear distance for being in a queue, the speed for delay below XX mph, the time for lead and lag safety zone for conflict checking, and the parameter values for the car-following equation. The available intersection control options to choose from are traffic signals with pretimed, semiactuated, or fully actuated controllers, all-way stop sign, two-way stop sign, yield sign, and uncontrolled.

Once SIMPRO has been successfully executed, the model can be prepared to display the simulation in graphics format. Two programs are used for this activity: DISPRE, which is a display preparation program, and DISPRO, which is the display processor in which the animated graphics are shown.

After running DISPRE, the program DISPRO is executed. This displays the intersection layout on the screen and then simulates the position of the vehicles from the time they enter the system to the time they leave it. This information can be displayed in real time or in a stop-and-go mode that is manually run. The graphic display is useful in detecting errors in the intersection geometry that may occur during the input of the offset of each leg centerline from the intersection center. It is also used to detect errors in the input of the phasing sequence for signalized intersections.

OBJECTIVE

The principal objective of this research study was to assess the ability of the TEXAS simulation model to simulate traffic movements at isolated signalized intersections using existing field data. This effort is needed to determine whether the model behaves in a way similar to the real world when run under the same conditions as the field data. The assessment process was attempted by comparing the results of the measures of effectiveness obtained from the simulation runs with those obtained from field data. Statistical methods were used to test the significance between the simulation and field results.

DESCRIPTIONS OF THE INTERSECTIONS

Eight intersection conditions, each having available field data, were used in this study. Six intersections located in the greater Phoenix area were used for the previous left-turn warrants study (*1*). The intersections were

- University and Alma School,
- Alma School and Broadway,
- Priest and Broadway,
- Thomas and 44th Street,
- Scottsdale and Thomas, and
- Dobson and Main.

These were chosen because they represented a wide variety of intersection characteristics. The intersections cover a range of values for the geometry such as the number of opposing lanes, the type of left-turn phasing, left-turn volume, and volume of opposing traffic. Table 1 presents selected data items for the six intersections. The near-side approach means the intersection approach at which the time lapse camera was placed.

Subsequent to the left-turn warrants study (*1*), the intersection of Thomas and 44th Street was operated under two other different scenarios. The original scenario had a pretimed signal with permissive left-turn phasing. The second scenario involved changing the left-turn phasing from permissive to exclusive-permissive (*2*). The signal was also changed to a fully actuated signal but with a variable cycle length that disrupted the vehicular progression. The third scenario had a phasing similar to the previous scenario but with a fixed cycle length that helped vehicular progression (*3*).

Therefore, a total of eight different intersection conditions were available for use. Two of the conditions address permissive left-turn phasing, two address leading exclusive left-turn phasing, and the remaining four conditions address lead-

TABLE 1 INTERSECTION DATA

Intersection Name	Major Street Near Side Approach			Major Street Far SideApproach			Control Type	Left Turn Control	No. of Phases	Major Street ADT (1984)
	No.of Inbound Lanes	No. of Outbound Lanes	Left Turn Pocket Lane	No. of Inbound Lanes	No. of Outbound Lanes	Left Turn Pocket Lane				
UNIVERSITY AND ALMA SCHOOL	3	2	YES	3	2	YES	PRETIMED	PERMISSIVE	2	26860
ALMA SCHOOL AND BROADWAY	3	2	YES	3	2	YES	ACTUATED	EXCLUSIVE/ PERMISSIVE	8	27210
BROADWAY AND PRIEST	4	2	YES	3	2	YES	ACTUATED	EXCLUSIVE	8	35400
44TH STREET AND THOMAS	4	3	YES	4	3	YES	PRETIMED	PERMISSIVE	2	43500
THOMAS AND SCOTTSDALE	3	3	YES	4	2	YES	ACTUATED	EXCLUSIVE/ PERMISSIVE	8	27860
MAIN AND DOBSON	4	3	YES	4	3	YES	ACTUATED	EXCLUSIVE	8	23100

ing exclusive-permissive left-turn phasing. Data collected for the eight different intersection conditions were used in this study.

Of the six different intersections being studied, three intersections have two opposing lanes that the left-turning vehicles have to cross, whereas the other three intersections have three opposing lanes to be crossed. This variety was intentional in the selection of the intersections because previous studies have shown that drivers making a left turn have greater difficulty in identifying acceptable gaps when there are three lanes of opposing traffic than when there are only two opposing lanes (*1*).

DATA COLLECTION

The TEXAS simulation model requires a considerable amount of input data. Extensive data collection is important for properly re-creating the field environment on the computer. These requirements help in minimizing errors that could develop in the later stages because of lack of data.

The data collected from the previous three studies (*1–3*) were used as the basis for this study and were complemented with more data collection. The extra data were needed because the three studies collected data for only two of the four approaches at each intersection. The data were collected in each of the previous studies by filming each one of the intersection scenarios using a time-lapse camera. Each scenario was filmed continuously for 7 or 8 hr during the day. This filming procedure captured morning and evening peaks as well as off-peak periods. The camera was situated about 300 ft in advance of the intersection. The location and orientation of the camera provided a good view of the two intersection approaches parallel to the camera's direction and of the middle of the intersection, but it was occasionally difficult to identify the green arrow indication and the green ball indication of the signal head. Nevertheless, side street volumes classified by turning movements were observed in the films. These volumes were used in simulating the actuated signal intersections. The filming was conducted on weekdays.

The data collected from the previous studies were for the two approaches parallel to the camera's field of view. The data included the number of vehicles stopped and the number of vehicles not stopping for each of the two approaches. Within each approach, these data were collected for the left-turn movement and for the through movement separately. For those studies, the definition of the through movement incorporated both the through and right turns (*3*). For each hour of filming, the data were set up in convenient 5-min intervals and were used to calculate stopped delay. Additional data collected for those studies included the signal timing plans and intersection geometry. Intersection configuration for the approaches perpendicular to the camera's field of view was obtained from city drawings that indicated the number of lanes, the lane widths, and the number and position of the loop detectors.

Additional data, not extracted from the film in the previous studies, were extracted. One kind of additional data was vehicle type. The TEXAS model has 12 different vehicle classes. For practical purposes, these were reduced to seven different classes, which were a sports car, a compact, a medium car, a large car, a single-unit vehicle using gas, a single-unit vehicle using diesel fuel, and a semitrailer. Viewer judgment was required in categorizing the vehicles viewed to their appropriate class. Trucks were usually categorized as single-unit vehicles using gas, whereas buses were categorized as single-unit vehicles using diesel fuel.

A second kind of additional data was headway distribution data. It was collected for the near-side approach parallel to the camera's field of view. The time between two successive free flowing vehicles was recorded for each open lane of the approach separately. The data were recorded for the vehicles traveling freely through the intersection during a green period and without slowing down because of a queue. When this condition occurred, the time when a lead vehicle passed a fixed point on the screen was recorded and the time that subsequent vehicles passed the same point was also recorded until the free flow state was interrupted. The difference between these recorded times gave the headway in seconds.

A third kind of additional data was a continuous record of signal timing. This data was collected randomly in 5-min intervals in each hour.

After acquisition of the additional data for the eight intersection conditions and the selection of the default values for the variables that had no data collected, the TEXAS model was used to simulate the intersection operation. For each set of conditions that were simulated, 15 replications were conducted, each using a different random seed. Mean values of the average stopped delay from the 15 replications produced by TEXAS were used to compare with the field stopped delay data acquired in the three previous studies.

Each of the eight intersection conditions was analyzed separately. The volume data for each intersection were divided into 10-min intervals. For each hour of film, the first five 10-min intervals were considered. The last 10-min interval was omitted because each film was not exactly 1 hr long and varied from 52 min in some cases to 59 min in others.

Preliminary Trial Runs

Another task that took place parallel to the data collection stage was using the TEXAS model to perform preliminary trial runs and a crude sensitivity analysis for some of the variables in the model. The purpose of this analysis was to have a better comprehension of the default values assumed in the model and to study how they affect the delay results. These trial runs were performed on the variables that would not have available data and so the default values of the TEXAS model were to be used. The variables to be considered were the parameters of the car-following equation, the different types of the headway frequency distribution, the percentage of left-turning vehicles in the median lane, the percentage of right-turning vehicles in the curb lane, the warm-up period, and other calibration variables used in the TEXAS model.

The trial runs were conducted on the intersection of Thomas and 44th Street with the pretimed signal condition, using the average volume data for the 2:00 p.m. hour, the observed vehicle classification, and using the default-shifted negative exponential as the initial headway distribution with a parameter of 1.0. For these runs, a warm-up time of 5 min was used, with a simulation time of 30 min. All other geometry and signal data required for the model were taken from the observed and previously documented data. This condition was chosen because the intersection was the first to be completed in the data collection phase. The runs were conducted to evaluate the effect of some of the model variables on the delay results.

Two of the variables were the percentage of left-turning vehicles in the median lane and the percentage of right-turning vehicles in the curb lane. The default values in the model were 80 percent for each variable; these were both changed to 100 percent and the model was run. The average stopped delay for all movements on both near-side and far-side approaches was recorded. The percentage difference was observed to range between −8.5 and +7.5 percent. Although this experiment only considered just one run with no statistical analysis, it appears that the two variables in question do not significantly affect the results. Because of lack of data availability concerning these two variables, it was decided to use the default values of 80 percent both for the percentage of left turners in the median lane and for the percentage of right turners in the curb lane.

The next variables considered were the lambda and alpha parameters of the car-following equation. Three runs were conducted with (a) changing the lambda value from the default of 2.8 to 2.4, and (b) changing the alpha value from the default of 4,000 to 6,000 and from 4,000 to 2,500. When each change was implemented, all other conditions and variables remained constant. The results from these three runs and the percentage difference that occurred with respect to the initial condition are presented in Table 2.

Closer examination of the results with lambda changed to 2.4 indicated that the change in the delay ranged from −16.0 to +129.8 percent. The range was between −16.0 and +12.9 percent for the right-turn movement and between −0.7 and +7.5 percent for the through movement, which did not seem significant. The major changes occurred for the left turns, which ranged from +129.8 to +11.5 percent. Changing the alpha parameter to 2,500 made the values of the percentage difference range from −44.2 to +2.8 percent. Again the wider range occurred for the left turns, ranging from −44.2 to −1.3 percent. The ranges for the through movement and right turns are closer together and are between −7.5 and +2.8 percent and −9.6 and −1.2 percent, respectively. The same observations are valid when the alpha parameter was changed to 6,000. To be able to conduct a statistical analysis on the attained results and draw some conclusions, a com-

TABLE 2 EFFECT OF CHANGING THE CAR-FOLLOWING EQUATION PARAMETERS ON THE AVERAGE STOPPED DELAY

Conditions	AVERAGE STOPPED DELAY (SEC)					
	Approach 1 (Southbound)			*Approach 2 (Westbound)*		
	Left	Thru	Right	Left	Thru	Right
Initial Condition (alpha = 4000, lambda = 2.8)	179.9	13.5	9.4	37.9	12.6	8.0
Change lambda to 2.4	228.1	13.7	7.9	87.1	12.8	9.0
Percentage Difference %	26.8	1.5	-16.0	129.8	1.6	12.5
Change alpha to 6000	200.4	14.4	8.8	49.6	12.8	8.1
Percentage Difference %	11.4	6.7	-6.4	30.8	1.6	1.3
Change alpha to 2500	100.3	13.2	8.5	22.5	12.5	7.8
Percentage Difference %	-44.2	-2.2	-9.6	-40.6	-0.8	-2.5
	Approach 3 (Northbound)			*Approach 4 (Eastbound)*		
	Left	Thru	Right	Left	Thru	Right
Initial Condition (alpha = 4000, lambda = 2.8)	186.9	14.1	8.4	22.3	12.0	9.3
Change lambda to 2.4	208.4	14.0	7.2	45.2	12.9	10.5
Percentage Difference %	11.5	-0.7	-14.3	102.7	7.5	12.9
Change alpha to 6000	227.9	13.7	6.9	28.3	12.3	8.6
Percentage Difference %	21.9	-2.8	-17.9	26.9	2.5	-7.5
Change alpha to 2500	154.2	14.5	8.3	22.0	11.1	9.0
Percentage Difference %	-17.5	2.8	-1.2	-1.3	-7.5	-3.2

prehensive sensitivity analysis is deemed essential, a task which is considered beyond the scope of this study. Nevertheless, the results indicate that the alpha and lambda parameters significantly affect the average stopped delay for the left-turn movements.

The fifth variable considered in these trial runs was the headway distribution. The default value used by the TEXAS model is the shifted negative exponential distribution with a parameter of 2.0. The parameter is defined as the minimum headway in seconds; it should be less than or equal to the mean headway. From the field headway data, the minimum headway was 1.0 sec, which was used for the parameter of the headway frequency distribution.

This distribution was compared with three other runs representing three different distributions. The other distributions considered were the gamma, the Erlang, and the negative exponential. The parameter required for the gamma was the square of the mean divided by the variance for the headway observations with the limitation that it must be greater than 1.0. From the field data, the calculated gamma parameter was 1.06. The Erlang parameter uses the same formula, but the limitation is that it must be an integer value greater than 1, so the parameter used was 2.0. The final distribution, which was the negative exponential, did not require a parameter.

The same pattern of results was noticed, namely that the range for the left turn was much wider than that for the through or right turn. The value of the percentage difference for the gamma distribution was observed between +66.4 and −40.5 percent, between −41.3 and +14.3 percent for the Erlang distribution, and between +40.0 and −25.1 percent for the negative exponential distribution. Without going into a detailed sensitivity analysis, the results indicate that the headway frequency distribution affects the average stopped delay. It is important to point out that the results of this analysis are limited to one intersection; including more sites in the analysis could possibly produce different conclusions.

For this study, the default shifted negative exponential headway frequency distribution was used, but with a parameter of 1.0 sec, which corresponds to the minimum headway observed. Again this decision was for practical reasons, because it is difficult, costly, and time consuming for a traffic engineer to conduct detailed headway data studies. Accuracy is an important factor because, for example, a change in grouping the data from 1- to 2-sec intervals could lead to a change from a gamma distribution to a shifted negative exponential, depending on the number of observations present in each interval.

The TEXAS model requires two time intervals before conducting the simulation, a warm-up time period and a simulation time period. The warm-up time is required so that the system can reach a steady or stable state before statistics are collected.

An experiment was designed to determine the sensitivity of the model to the length of the warm-up period and the length of the simulation time. In this experiment, both warm-up time periods and simulation time periods were changed. The volume for a 10-min period and the random number seed combination were kept constant. The simulation period was set at 10 min and then changed by being increased in 5-min increments up to 30 min. The time was not increased further because of the approach volume limitation of the TEXAS model. For each simulation period, the warm-up time was increased from 2 to 10 min in 1-min increments and the results were documented.

The ratio of the warm-up time to the simulation time was compared with the ratio of the number of vehicles processed during the warm-up period to the number of vehicles processed during the simulation period. Steady or stable state was assumed to occur when the difference between the two ratios was small. The definition of a processed vehicle in the TEXAS model is a vehicle that both enters and leaves the intersection system. When it leaves that system, it is considered to have been processed and statistical results for the vehicle are recorded.

The warm-up time runs were conducted for the fifth 10-min interval in the 4:00 p.m. film of the intersection of Thomas and 44th Street, which had a two-phase pretimed signal with a cycle length of 50 sec. This intersection was used because all the required data were collected for that intersection and the time interval chosen was the most critical one in the afternoon peak period. The results presented in Table 3 indicate that a warm-up period of 8 min is the optimum case for shorter simulation periods of 10 to 15 min, whereas a 9- to 10-min warm-up period is better for longer simulation periods of 20 to 30 min. No significant trends were observed and the percentage change value was not stabilizing as simulation periods became longer.

The warm-up time was further increased from 10 to 15 min using 1-min increments but still no trend was observed. Further investigation of the warm-up experiment was beyond the scope of this study. The stability of the warm-up period is certainly sensitive to the left-turn phasing. The user manual of the model recommends a warm-up period of 2 to 5 min depending on the traffic volumes. Because for most of the intersection conditions studied the volumes were usually above 1,000 vehicles per hour, a 5-min warm-up period was used.

The TEXAS model automatically produces a random number seed if the user failed to input one. The problem with using the default seed is that when a new run is initiated, the model will produce the same random number seed. This process results in the generation of the same arrival pattern. To change this default seed, the random number seed was entered as part of the data and changed each time a new run was done. To ensure that the seed selection was random, the numbers were generated from an external random number generator using the GWBASIC program found in MS-DOS. A subroutine was written to generate a random number table of 5 columns and 15 rows. The first column was used as the random number seed for the first approach and the second column for the second approach up to the fourth column for the fourth approach. The 15 rows corresponded to the random number seed for the 15 runs. When the initial 15 runs were completed, a few runs gave errors because of the random seed combination. To remedy this problem, the random number columns used were shifted one space for that particular run.

The last set of test runs was conducted to test the impact of selected calibration variables on the model output. Three variables were identified: the driver operational factor for different driver classes (IDCHAR), the operating characteristics for different vehicle classes (IVCHAR), and the perception-reaction time for different driver classes (PIJR). Several computer runs were conducted using the extreme val-

TABLE 3 RESULTS OF THE WARM-UP PERIOD EXPERIMENT

	THOMAS AND 44TH STREET WARM UP TIME (MIN.)									
SIM TIME (MIN.)	2	3	4	5	6	7	8	9	10	
10	.2	.3	.4	.5	.6	.7	.8	.9	1	Warm up/simulation (time)
	.11529	.24540	.32380	.45802	.57641	.63882	.78645	.81119	.93772	Warm up/simulation (vehicles)
%Change	42.354	18.2	19.050	8.3910	3.9351	8.7399	1.6944	9.8679	6.2275	% Change
15	.13333	.2	.26667	.33333	.4	.46667	.53333	.6	.66667	Warm up/simulation (time)
	.09434	.16223	.22846	.28413	.34852	.45891	.52573	.58632	.624	Warm up/simulation (vehicles)
% Change	29.245	18.885	14.328	14.762	12.870	1.6622	1.4258	2.2797	6.4	% Change
20	.1	.15	.2	.25	.3	.35	.4	.45	.5	Warm up/simulation (time)
	.06790	.12666	.16687	.20977	.28633	.31075	.38168	.43075	.48635	Warm up/simulation (vehicles)
% Change	32.102	15.558	16.564	16.091	4.5558	11.215	4.5790	4.2777	2.7295	% Change
25	.08	.12	.16	.2	.24	.28	.32	.36	.4	Warm up/simulation (time)
	.05699	.09339	.13780	.17336	.21384	.25208	.29217	.33446	.38204	Warm up/simulation (vehicles)
% Change	28.756	22.179	13.877	13.320	10.901	9.9699	8.6977	7.0955	4.4890	% Change
30	.06667	.1	.13333	.16667	.2	.23333	.26667	.3	.33333	Warm up/simulation (time)
	.04631	.07905	.11142	.14932	.18881	.20974	.24202	.29031	.31167	Warm up/simulation (vehicles)
& Change	30.533	20.947	16.433	10.405	5.5944	10.113	9.2424	3.2302	6.4998	% Change
35	.05714	.08571	.11429	.14286						Warm up/simulation (time)
	.04084	.06625	.09789	.12617						Warm up/simulation (veh. proc.)
% Change	28.534	22.708	14.342	11.681						% Change

ues suggested for these variables and little or no changes were observed in the left-turn delay statistics. The reason for the little changes in the results is that all six intersections are heavily traveled and changes in the driver behavior or vehicle characteristics have limited impact on the intersection capacity. Closer examination of the left-turning maneuvers, using the animation option of TEXAS, indicated that the model is incapable of simulating the left-turn laggers.

Determining the Critical Time Periods

Each intersection was divided into 35 to 40 ten-minute time intervals depending on the number of hours of film (7 or 8) for each location. The process of taking every interval (approximately 35 intervals) and running it 15 times (15 replications) for each intersection condition would have been extremely time consuming. Therefore it was decided to choose representative intervals that would be the most critical for each intersection.

The procedure undertaken was to arrange the 35 to 40 ten-minute approach volumes for the near-side approach of an intersection in ascending order. The emphasis was on the two approaches parallel to the camera's field of view because they were the ones for which average stopped delay was calculated in the previous studies. Table 4 indicates this procedure. The table contains a column for the left-turn volume of the near approach, the percent of left turns, the volume of the opposing approach, the cycle length, and the product parameter.

The product parameter is reached by multiplying the approach volume by the percentage of left turns in decimal form and by the opposing volume. The range of the approach volume is divided into 6 to 8 intervals and a frequency table is generated as indicated in Table 4. Out of each frequency interval, the critical reading is selected on the basis of the greater value of the product parameter. This was the basis for the selection procedure of the critical 10-min time periods. The actual selection differed somewhat depending on the type of left turn phasing at that particular intersection.

For permissive left-turn phasing, the most critical parameter is the volume on the opposing approach. Therefore, for this condition the critical 10-min time period chosen in each interval is the one satisfying the greater value of the product parameter. If one of the intervals has more than one cycle

TABLE 4 SELECTION OF THE CRITICAL 10-min PERIODS

Intersection: **Alma School & Broadway (Exclusive/Permissive Left Turns)**

Approach: **Northbound (leg 3)**

Hourly Volume (VPH)	*Left Turn Volume*	*Percent of Left Turns*	*Opposing Volume (VPH)*	*Product Parameter*		*Frequency*	*Table*
765	107	14	900	96390		750-850	2
786	165	21	1128	186188	---1	850-950	7
858	129	15	858	110425		950-1050	10
864	147	17	774	113685		1050-1150	10
888	186	21	1050	195804	---2	1150-1250	7
912	128	14	792	101123		1250-1350	4
930	140	15	990	138105			
942	170	18	930	157691		Maximum Cycle Length = 148.5 seconds	
948	142	15	864	122861			
954	153	16	930	141955			
954	181	19	924	167484			
954	105	11	954	100113			
960	154	16	1128	173261			
978	137	14	888	121585			
996	100	10	804	80078			
1002	160	16	1434	229899	---3		
1014	172	17	930	160313			
1044	188	18	810	152215	---4		
1044	146	14	870	127159			
1068	171	16	1158	197879			
1068	182	17	1344	244017			
1080	173	16	978	168998			
1086	185	17	1134	209359			
1098	285	26	1236	352853	---5		
1104	188	17	1098	206073			
1116	246	22	1116	274000			
1134	91	8	1446	131181			
1140	160	14	1266	202054			
1146	218	19	954	207724			
1152	207	18	1446	299843			
1158	151	13	1572	236649			
1158	139	12	1512	210108			
1164	128	11	1140	145966			
1170	140	12	1350	189540			
1194	96	8	1452	138695			
1194	215	18	1308	281115	---7		
1272	191	15	1140	217512			
1290	232	18	930	215946	---8		
1320	198	15	984	194832			
1332	173	13	918	158961			

length, the selection process is conducted for each value of the cycle length separately.

The critical parameter for the exclusive-permissive left-turn phasing is also the volume on the opposing approach for the permissive part and the left-turn volume on the near approach for the exclusive part. The selection process for this case involves finding, within each interval, the 10-min period that has the greater value of the product parameter and at the same time the greater value of the left-turn volume on the near approach. The best selection is a 10-min period that satisfies both criteria. If this is not possible, then two 10-min periods are selected—one for each criteria. Again, if there is more than one cycle length in the interval, the selection is conducted for each cycle length separately.

For the exclusive left-turn phasing, the critical parameter is the left-turn volume on the near approach. The selection criterion for this condition is the greater value of the left-turn volume on the near approach. Usually this 10-minute period would have a high value for the product parameter but not necessarily the greater value. When there is more than one cycle length in each interval, the selection is conducted for each cycle length separately.

Table 5 presents the findings of the selection process for all eight intersection conditions. A total of 87 critical 10-min periods were selected and each one of the periods was run 15 times using the TEXAS model resulting in 1,305 individual runs.

TABLE 5 SUMMARY OF THE CRITICAL TIME PERIODS SELECTED

Intersection Condition	Number of Intervals	Number of 10 min Periods Selected
University and Alma School	9	11
Alma School and Broadway	6	8
Priest and Broadway	10	8
Thomas and 44th Street	7	10
Stonex's Scenario	8	12
Warne's Scenario	9	15
Scottsdale and Thomas	7	14
Dobson and Main	7	9

Running The Model

Once this stage was completed for each intersection condition, it was time to run the model and document the results. For each one of the selected 10-min periods, the corresponding 10-min volume for the approaches parallel to the camera's field of view was adjusted to an hourly volume. The data relevant to each 10-min period were keyed into the TEXAS model, i.e., the geometry, driver-vehicle data, and simulation data. The model was run 15 times for each particular case with the replacement of the random number seed for each approach being the only change conducted from one run to the next. For each run, a warm-up period of 5 min and a simulation period of 10 min were used. After the model had completed execution, the results for the required variables were documented and keyed into a spreadsheet. The results that were of importance to this study were the average stopped delay for each movement on the approaches that were parallel to the camera's field of view. The output of the TEXAS model gives extensive results for each movement on each approach as well as summary results for each approach and for the whole intersection. Only the two approaches parallel to the camera's field of view were considered for comparison because the field data from the previous studies were only for those two approaches.

The decision of using a warm-up period of 5 min and a simulation period of 10 min was achieved from the sensitivity analysis conducted for the Thomas and 44th Street intersection. The signal cycle length at that intersection is 50 sec. Five-minute warm-up period and 10-min simulation period would result in 6 and 12 complete cycles of simulation, respectively. It was felt that these two periods are suitable to produce steady state conditions at most of the intersections. Increasing the simulation period would have required much longer computer time, and it was not clear how much improvement in the results would have been achieved.

The only intersection that should be treated with some caution is Alma School and Broadway. The traffic signal system for this intersection is composed of a fully actuated eight-phase controller with a maximum cycle length of 148.5 sec. If the cycle reaches the maximum value consistently during the warm-up and simulation period, then it would result in two and four complete cycles, respectively. The results of this analysis may become questionable. The type of left-turn phasing at this intersection is exclusive-permissive. There are three other intersection conditions for exclusive-permissive left-turn phasing and they all have much shorter cycle length.

RESULTS AND ANALYSES

In order to display the results in a logical form, the eight intersection conditions are grouped by the type of left-turn phasing. This grouping is appropriate because the validation process emphasized the type of left-turn phasing. The intersection conditions of Alma School and Broadway, Stonex's (*2*) scenario, Warne's (*3*) scenario, and Scottsdale and Thomas all had an exclusive-permissive left-turn phase. The intersection conditions of University and Alma School and 44th Street and Thomas had a permissive left-turn phase. Finally, the intersection conditions of Broadway and Priest, and Dobson and Main, had an exclusive left-turn phase. The following section contains the results for one out of the eight intersection conditions. A summary of all statistical results is documented in a later section.

Results of Alma School and University (Permissive Left-Turn Case)

The number of critical 10-min periods selected were 11 for Alma School and University. The results obtained from running the TEXAS model 15 times for each 10-min period are presented in Table 6. Each average stopped delay value for the left-turn movement and for the through movement is the mean of the 15 runs for that time period.

Examining the results, both the eastbound approach and the westbound approach have similar trends. The mean stopped delay of the 11 time periods for both left turns obtained from the simulation are more than three times the mean stopped delay obtained from the field and presented in the observed column. The left-turn standard deviation for the simulation results are 61.5 and 76.2 sec, respectively, whereas the standard deviation for the field results are 15.3 and 13.3 sec, respectively. The through movements have the mean stopped delay for the simulation within 2 sec of the field results; the standard deviation for the mean stopped delay in the field is at least 4 times greater than in the model. The simulation results indicate that there is a higher variation in the delay between the different time periods for the left-turn movement than for the through movement on the same approach. This variation is not that extreme for the observed delay data.

A reason for the high variation in left-turn delay results in the model is because of the fact that left-turn movements take place when opposing through traffic is outside a conflict region. Therefore, the delay results vary depending on the combined effect of the opposing volume and the arrival pattern of the opposing traffic. This explanation is not applicable for the through movement; so the delay results are narrowly spread within a small range. For the left-turn movement, the delays from the model are high compared to the field delay because the model does not accurately represent driver behavior. The conflict region explanation is more conservative than gap acceptance where a left turn would be made when an appropriate gap occurs in the opposing traffic. In addition, the model makes left-turning vehicles stop at the stop bar and therefore only one vehicle can turn during the yellow phase per cycle. Field data indicated that two, and in some cases three, sneakers turned left during the yellow phase. Another

TABLE 6 AVERAGE STOPPED DELAY RESULTS FOR ALMA SCHOOL AND UNIVERSITY FOR PERMISSIVE LEFT TURNS

Eastbound Approach*			*Average Stopped Delay (sec)*							
Left Turn Volume (VPH	Opposing Volume (VPH)	Time of Day	Eastbound Approach				Westbound Approach			
			Left Turn		Through		Left Turn		Through	
			Sim	Obs	Sim	Obs	Sim	Obs.	Sim	Obs
35	942	8:35 am	29.8	10.5	14.0	12.4	25.9	36.7	14.4	14.0
75	660	8:45 am	33.9	26.0	14.5	11.7	30.7	45.0	14.8	15.5
91	786	8:55 am	39.2	15.0	14.4	13.9	35.9	24.5	14.5	17.5
67	864	9:40 am	109.7	11.4	15.0	15.9	56.9	19.0	15.3	16.7
113	948	10:50 am	113.8	42.0	14.5	18.5	62.8	35.0	15.9	20.0
76	1278	11:30 am	180.1	24.5	16.1	19.2	179.1	57.7	15.5	13.2
93	996	1:50 pm	80.8	32.3	15.0	17.0	109.8	35.0	14.6	13.1
155	918	2:00 pm	31.8	14.5	14.2	13.3	50.7	19.2	14.3	11.5
127	1158	2:45 pm	90.3	33.1	14.5	16.9	90.4	28.0	13.9	11.9
114	1266	3:50 pm	147.2	48.2	17.0	35.8	222.6	-----	16.5	19.2
114	1245	4:20 pm	187.3	50.8	16.1	16.0	206.5	-----	16.5	23.3
Mean Delay			94.9	28.0	15.0	17.3	97.4	33.3	15.1	16.0
Std. Dev.			61.49	15.26	1.00	6.90	76.22	13.29	0.94	3.91

----- Not Available
*Time lapse Camera's Position

possible reason is that real-world driver behavior tends to be more aggressive than anticipated and depends on many factors.

The data points are graphically represented and are shown in Figures 1 and 2. Each figure has the simulated delay data plotted against the observed delay. On the same graph, a line that has a slope equal to unity is drawn that represents the plotting of the observed delay data against itself. The scatter plot indicates how much the simulated delay data deviates from the observed delay data. Evidence that the simulation model performs well would be found if the simulated data points fall on or closely around the unit slope line. Figure 1 shows the results of the eastbound left-turn delays with all the data points falling above the unit slope line. Figure 2 shows the results of the eastbound through delays in which the data points fall above and below the line and are grouped in a small range.

Figures 1 and 2 suggest, but do not prove, that the simulation model works well in some cases, and performs poorly in other cases in predicting average stopped delay. To prove or disprove that the model works well, statistical tests were used. The null hypothesis was that the difference between the observed average stopped delay (from field data) and the simulated average stopped delay (TEXAS model) equals zero. The paired-data *t*-test was adopted for the statistical analysis and the results are presented in Table 7. The mean of the differences and the standard deviation are used to obtain the calculated test statistic *t*. The results of the statistical analysis indicate that for a level of significance of 0.05 the null hypothesis was rejected for both eastbound and westbound left turns. The null hypothesis was not rejected for the through movements and on conducting the β test, the probability of accepting the null hypothesis was greater than 0.75. Therefore it was decided to accept the hypothesis that the difference between the observed means and the simulated means equals zero for both the eastbound and westbound through movements at a confidence level of 0.05. This finding suggests that for this intersection, the model does a good job in simulating the through movements; however, simulating left-turn movements appears to be inconsistent with the field data.

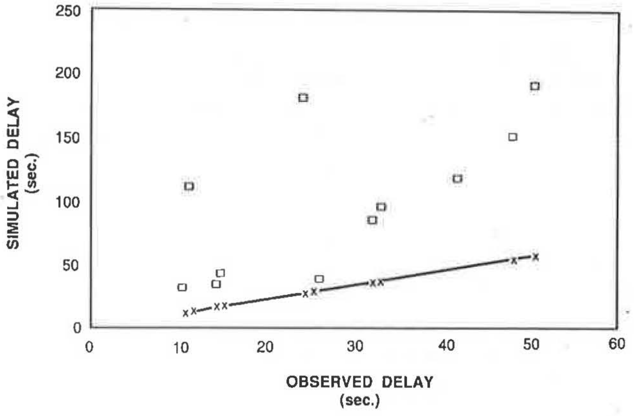

FIGURE 1 Alma School and University eastbound permissive left-turn results.

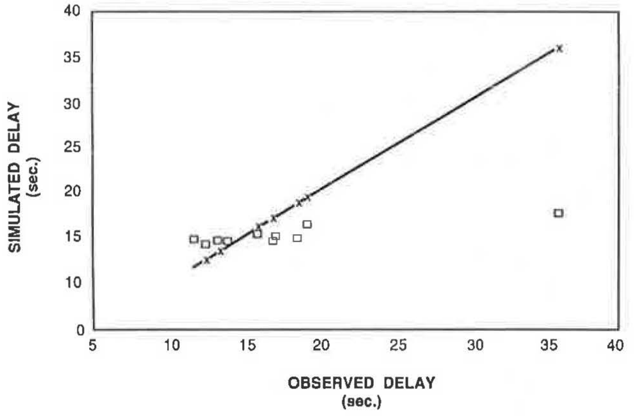

FIGURE 2 Alma School and University eastbound permissive through results.

TABLE 7 PAIRED-DATA *t*-TEST RESULTS FOR ALMA SCHOOL AND UNIVERSITY FOR PERMISSIVE LEFT TURNS

Time of Day	Difference Between Simulated and Observed Delay Results (sec)			
	Eastbound Approach		Westbound Approach	
	Left Turn	Through	Left Turn	Through
8:35 am	19.31	1.62	-10.81	0.36
8:45 am	7.94	2.85	-14.32	-0.67
8:55 am	24.19	0.50	11.37	-3.00
9:40 am	98.29	-0.87	37.94	-1.33
10:50 am	71.77	-4.01	27.76	-4.14
11:30 am	155.62	-3.09	121.41	2.28
1:50 pm	48.52	-1.94	74.77	1.46
2:00 pm	17.31	0.90	31.54	2.79
2:45 pm	57.20	-2.39	62.36	2.03
3:50 pm	99.01	-18.77	----	-2.63
4:20 pm	136.52	0.12	----	-6.75
Mean Difference	66.88	-2.28	38.00	-0.87
Standard Deviation	52.67	6.14	35.74	3.18
t calculated	4.212	-1.231	2.755	-0.911
Conclusion	reject H_0	cannot reject H_0	reject H_0	cannot reject H_0
Probability to Accept $H_0(1-\beta)$	———	0.83	———	0.89

Note: $n = 11$, $t_{(0.025,10)} = 2.228$

Results of the Permissive Left-Turn Combined Data

The statistical analyses of the second permissive left-turn phasing intersection (Thomas and 44th Street) indicated similar results to those of Alma School and University intersection. In both cases it was concluded that the TEXAS model overestimates delay for left-turn movements. This finding was previously shown in Figures 1 and 2 where points were scattered above the unit slope line. It was decided to combine the data of both intersections and attempt to fit a linear regression line for those scattered points. If a straight line parallel to the unit slope line is successfully fit, then this line and the new line would measure the average deviation between the field data and the TEXAS model results. Linear regression was conducted to fit a line to the scattered data points. The slope coefficient was statistically tested with the null hypothesis stating that the slope coefficient equals 1. If the null hypothesis is accepted, then the regression line through the data points is parallel to the unit slope line, but it is shifted upward at a certain value equal to the value by which the model overestimates delay. Results of the regression analyses are presented in Table 8. The statistical test conducted to find out if the slope coefficient equals 1 were all rejected except for the left-turn delay data for the near-side approach. A β test was conducted; the probability of accepting the null hypothesis that the slope coefficient equals 1 was 0.93. Therefore it is safe to say that the left-turn delays for the near-side approach obtained from the TEXAS model follow the same trend as the observed left-turn delay results for the same approach but with an increased delay of 66.8 secs.

Results of the Exclusive-Permissive and Exclusive Left-Turn Cases

The statistical analysis procedure applied to the two permissive intersection cases was also applied to the exclusive-permissive and exclusive left-turn cases. For exclusive-permissive left-turn phasing, four intersection cases were analyzed. In all four cases, it was observed that the model overestimates delay for left-turn traffic.

As for exclusive left-turn phasing, two intersections met the criteria, and the statistical analyses indicated that the model overestimates delay for left-turn traffic. Comparing the differences between the simulated and observed field data across all three types of left-turn phasing, it was concluded that the differences were the greatest for permissive phasing, smaller for exclusive-permissive phasing, and the least for exclusive phasing. Naguib (7) provided detailed information concerning the results.

A summary of all the statistical results for the eight intersection cases and the combined data is presented in Table 9. The significant conclusion reported for the eight intersection cases means that the simulated mean stopped delays produced by the TEXAS model are significantly different than the mean stopped delays observed in the field at a level of confidence of 95 percent.

TABLE 8 REGRESSION ANALYSIS RESULTS FOR PERMISSIVE LEFT-TURN PHASING

Parameters	Near Side Approach		Far Side Approach	
	Left Turn	Through	Left Turn	Through
Slope Value	1.132	0.231	1.814	0.227
Std. Error of Slope	0.266	0.075	0.330	0.066
Intercept Value	66.82	11.72	17.52	11.37
R Squared	0.489	0.331	0.640	0.380
t calculated	0.495	-10.226	2.467	-11.659
Conclusion	cannot reject H_o	reject H_o	reject H_o	reject H_o
Probability to Accept Ho (1-β)	0.93	———	———	———

Notes : H_o: $b_1 = 1$ (slope is unity), H_a: $b_1 = 1$ (slope is not unity)
$n = 21$, $t_{(0.025,19)} = 2.093$

TABLE 9 SUMMARY OF STATISTICAL RESULTS

Approach		Near Side		Far Side	
		Left Turn	Through	Left Turn	Through
Permissive	Alma School and University	S	N.S.*	S	N.S.*
	Thomas and 44th Street	S	S	S	N.S.
Exclusive/ Permissive	Alma School and Broadway	S	N.S.*	N.S.*	N.S.*
	Stonex's Scenario	S	S	S	N.S.
	Warne's Scenario	S	N.S.*	S	N.S.*
	Scottsdale and Thomas	S	N.S.*	N.S.	N.S.*
Exclusive	Broadway and Priest	S	N.S.*	S	N.S.*
	Dobson and Main	S	S	S	S
Combined Data	Permissive	N.S.*	S	S	S
	Exclusive/ Permissive	N.S.	S	N.S.	S
	Exclusive	N.S.*	S	N.S.*	S

Notes: S -denotes a significant conclusion from the null hypothesis.
N.S. -denotes a non-significant conclusion from the null hypothesis.
* -denotes it also passed the β-test criteria.

The combined data includes the three left-turn phasing treatments. The permissive left-turn treatment combines two intersection results, the exclusive-permissive treatment combines four intersection results, and the exclusive treatment combines two intersection results. The significant conclusion reported for the combined data means that the regression line fitted to the delay data produced by TEXAS has a slope significantly different from unity at a level of confidence of 95 percent.

Table 9 indicates that all the near-side left-turn delays rejected the null hypothesis that they do not differ from the observed delay, while all the through delays for the combined data were not parallel to the unit slope line. This finding may appear negative. The nonsignificance conclusion means that the left-turn delay estimated by the TEXAS model follows the same trend as the observed delay results. It is a positive finding because one can determine the deviation between the two lines and use it for calibrating the different variables of the model.

CONCLUSIONS

The main goal of this study was to test the TEXAS model, as provided to the users without changing its default parameters, against field data.

The limited number of trial runs indicated that the percentage of left-turning vehicles in the median lane and the percentage of right-turning vehicles in the curb lane had no significant effect on the left-turn and through delay figures.

However, the alpha and lambda parameters of the car-following logic were found to have significant impacts on the average stopped delay, especially for the left-turn movement.

The headway distribution used in the model to generate vehicles was found to have a significant impact on the delay results. The user is advised to collect field data on headway distribution to fit it to one of the distributions provided by the TEXAS model. As for the warm-up period, it was concluded that a more detailed experiment is needed to identify the region of steady state for different left-turn phasing schemes.

The statistical results concluded that the TEXAS model is capable of simulating through movements fairly well. The ability of the model to graphically display intersection geometrics and to provide animation of traffic movements was certainly helpful in coding the data properly.

The results further indicated that delay figures estimated for left-turn traffic were higher than those observed in the field for all three types of left-turn signal phasing (permissive, exclusive-permissive, and exclusive). The difference between the model results and the field data was found to be the greatest for permissive phasing and the smallest for exclusive phasing. It is believed that the permissive left-turn logic needs some refinements. Closer examination of the data revealed that the TEXAS model does not simulate left-turn laggers. Furthermore, vehicles who are attempting a left turn during a permissive phase are queued behind the stop bar, and not permitted to enter the intersection until an acceptable gap in the opposing traffic is presented.

Although the simulated delay figures were significantly different than the field data figures, all three types of left-turn phasing indicated that the delay estimated by the TEXAS model followed the same trend as the observed delay results.

ACKNOWLEDGMENT

The authors would like to acknowledge the Arizona Department of Transportation for sponsoring this research project.

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Views expressed in this paper are those of the authors and not of the Arizona Department of Transportation. The authors are responsible for the accuracy of the results presented in this paper.

Publication of this paper sponsored by Committee on Traffic Flow Theory and Characteristics.