Analysis of Intersection Capacity and Level of Service by Simulation

Clyde E. Lee, University of Texas at Austin
Vivek S. Savur, Valparaiso University, Valparaiso, Indiana

A procedure for applying computer simulation in evaluating the capacity and level of service of single, unsignalized intersections is presented. The process may also be used to study these features at signalized intersections. The TEXAS model for intersection traffic is especially suitable for this purpose because it (a) uses a detailed description of intersection geometry, (b) incorporates as many as 5 driver and 15 vehicle classes in the traffic stream, (c) simulates the behavior of each individually characterized driver-vehicle unit as it responds to its static and dynamic surroundings, and (d) presents summary statistics about the performance of traffic and traffic control devices at the end of any selected period of time. Capacity, which is the maximum traffic volume that can be accommodated under prevailing conditions on an intersection approach or by the whole intersection, can be determined through a successive approximation technique by using a few runs of the model. The level of service of an intersection operating under a specified form of control and carrying a given traffic volume can be defined in terms of recommended quantitative indicators such as average delay, percentage of vehicles required to stop, and percentage of vehicles required to slow to less than 16 km/h (10 mph). Four cases in which the model can be used to determine the capacity and level of service of unsignalized intersections are presented.

The maximum volume of traffic that can be handled by a road or street network is frequently limited to that which can flow through a single intersection. Capacity analysis of road segments that include intersections thus involves two basic steps:

1. Critical, or bottleneck, intersections must be identified and their capacity determined and
2. The overall traffic-carrying capability of the road section can then be appraised.

Thus, a practical, effective means is needed for evaluating the capacity of a single intersection operating under any given form of traffic control.

The capacity of an intersection is defined as the maximum number of vehicles that can pass through the intersection during a given period of time under prevailing roadway, environmental, and traffic conditions (1, p. 129). Capacity is not a constant quantity but depends on a number of factors, some of which are static (e.g., intersection geometry and traffic control devices) and others of which are dynamic (e.g., moving vehicles and pedestrians). At a particular time, the maximum flow on an intersection approach, or through the intersection as a whole, might be considerably different than at another time because of different traffic patterns or other dynamic factors. Analysis of intersection capacity involves evaluating the combined effects of both static and dynamic influences and defining the maximum volume that can be accommodated on each intersection approach under the stated conditions without specific regard for the degree of satisfaction that will be experienced by the driver. When it operates at capacity, an intersection usually provides relatively poor service from the viewpoint of the user.

Level of service is a phrase used by transportation engineers to describe the subjective appraisal that a representative driver will give to the quality of traffic flow provided by an intersection approach. Associated with each service level is a service volume—the maximum volume the intersection can accommodate while providing the specified level of service. If satisfied with the manner in which traffic moves through the intersection, the driver will say that a high level of service is provided; if dissatisfied, the driver will indicate a low level of service. Experience has shown, however, that what is judged to be excellent service under one set of circumstances at one location may well be described qualitatively as poor service in a different situation. Quantitative indicators that differentiate various levels of service under defined conditions are needed to make communication among transportation professionals easier and to achieve consistency in intersection evaluation and design.

The methods currently available for analyzing intersection capacity and levels of service are generally 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 use statistical distributions to represent traffic characteristics such as headway, spacing, and speed. Expected interactions among traffic streams at the intersection are then computed and presented as graphs or formulas for capacity. Observation methods involve field sampling and forecasting. Time-lapse photography has been used successfully to record traffic movements at representative intersections; then, data from the pictures have been analyzed and reduced to formulas for capacity. These methods have usually been applied to capacity evaluation of signalized intersections on a macroscopic scale.

No means other than direct observation has been available for studying, on a microscopic scale, intersection capacity as it is affected by the behavior of individually characterized driver-vehicle units operating in the partly static, partly dynamic intersection environment. Recent advances in digital computer technology now make this possible, however, through simulation. The expected interaction among the four primary elements of intersection traffic flow—the driver, the vehicle, the roadway, and the traffic control—can be analyzed by computer simulation in considerable detail and in a highly compressed time frame. A particularly suitable simulation package for this purpose is the traffic experimental and analytical simulation (TEXAS) model for intersection traffic (2-6), which was developed at the Center for Highway Research at the University of Texas at Austin especially for analyzing traffic performance at single, multileg, mixed-traffic intersections that operate either without control devices or with any conventional sign or signal control scheme.

This paper describes how results of simulation with the TEXAS model have been used as the basis for selecting suitable quantitative indicators of level of service and for developing a procedure for determining the capacity and level of service of unsignalized intersections. Only a few runs of the model are required to evaluate the expected performance of the geometric configuration, control scheme, and traffic pattern of any selected intersection.

OPERATION OF THE MODEL

The TEXAS 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 are based on probability. Traffic input to the modeled intersection approaches is generated on a stochastic basis from descriptive information provided by the user. Arrival headways are generated by a preprocessor in the computer program as random variates of a user-selected probability distribution function. Then, when precise criteria required for a particular driver-vehicle response are satisfied, a programmed action is carried out. Each driver-vehicle unit in the intersection area is examined sequentially during a short time interval (e.g., 0.5 s) and advanced to its next position.

The simulated intersection 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.

On request, a large variety of information concerning the results of simulation can be printed, punched on cards, or shown on a graphics display screen. The data can be produced for each traffic movement separately, according to approach, or they can be summarized for the whole intersection.

The items of output that have been used in this paper for quantifying capacity and level of service at unsignalized intersections are (a) total intersection volume, (b) percentage of vehicles required to stop, (c) percentage of vehicles required to slow to less than 16 km/h (10 mph), (d) average queue delay, and (e) average stopped delay.

LEVEL-OF-SERVICE INDICATORS

The level of service at intersections depends on the manner in which traffic flows through the intersection. At signalized intersections, load factor is widely accepted as a performance indicator for level of service (1). Load factor is defined as the ratio of the total number of fully used green signal intervals in a series of signal cycles to the total number of green intervals for that approach during the same period. 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 present throughout the phase and the total number of green phases displayed in a selected time period. Load factor is the ratio of these two numbers. Numerical limits of load factor for various levels of service are given below (1):

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

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

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, whereas the user may prefer more subjective measures of satisfaction. Indicators related to both 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 or her 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 indicators discussed below appear to be appropriate measures of level of service at unsignalized intersections in that they incorporate all of these desired features.

Queue Delay

Queue delay is the time spent by a vehicle at a virtual stop in a queue on an intersection approach. A vehicle can be said to be in a queue when it is within, say, 10 m (33 ft) of another vehicle, or some other object, ahead that requires a stop and when it is stopped or moving less than 3 km/h (2 mph). Queue delay begins when the vehicle joins a queue and ends when the vehicle enters the intersection.

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 3 km/h (2 mph) as it moves forward in the queue. Queue delay thus 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 spend a minimum of time waiting in a queue while traveling through an intersection. Since 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 by (a) a count of the number of vehicles in the queue at fixed, periodic time intervals (point sample), (b) the input-output method, (c) a path trace based on a sample of individual vehicles, and (d) time-lapse photography. A special device for recording queue delay by the point-sample technique on a 1-s time basis is described by Lee, Rioux, and Copeland (2).

A recent study by Sutaria and Haynes (7) used the opinions of 310 drivers who had 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: (a) delay, (b) number of stops, (c) traffic congestion, (d) number of trucks and buses in the traffic stream, and (e) difficulty of changing lanes. Each driver was then shown a series of photographs of a signalized intersection in Dallas that was 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.

Percentage of Vehicles Required to Stop

The percentage of vehicles that are required to stop is easy to measure in the field by simply 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 functions 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 of vehicles required to stop is easier to measure than average queue delay, it might be preferable to intersection designers as a level-of-service indicator. It is applicable primarily at uncontrolled and yield-sign-controlled intersections, however, since, 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 essentially as a stop-sign-controlled intersection can be observed because, at that point, a high percentage of vehicles are required to stop.

Figure 1. Levels of service at four-lane by four-lane, all-way stop-sign-controlled intersection: service volume versus average queue delay.

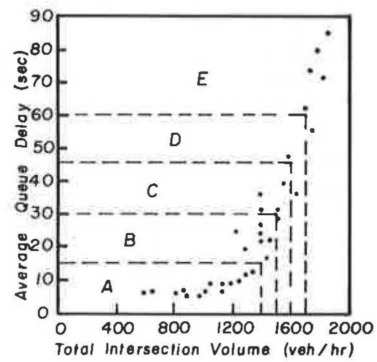


Figure 2. Levels of service at yield-sign-controlled intersection: percentage of vehicles on signed approaches slowing to less than 16 km/h versus average queue delay.

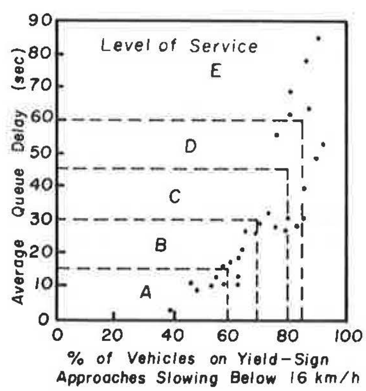
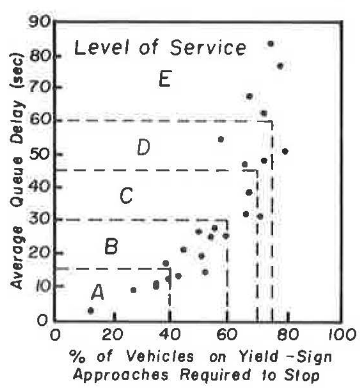


Figure 3. Levels of service at yield-sign-controlled intersection: percentage of vehicles on signed approaches required to stop versus average queue delay.



Percentage of Vehicles Required to Slow to <16 km/h (<10 mph)

The percentage of vehicles that must slow to less than 16 km/h (10 mph) relates directly to driver satisfaction since no driver likes to slow to less than 16 km/h. This indicator is difficult to determine in field studies, however. It can possibly be measured in the field by using time-lapse photography. The TEXAS model allows the user to specify the minimum desirable speed, and then the percentage of simulated vehicles that traveled at less than this speed is computed. Thus, a statistic is available for comparing the performance of various types of unsignalized intersections. A further incentive for considering this indicator is that the 1971 Manual on Uniform Traffic Control Devices (MUTCD) (8, p. 34) states the following:

> 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 [16 km/h] 10 miles per hour.

RELATING SELECTED PERFORMANCE INDICATORS TO LEVEL OF SERVICE

Since queue delay can be used as an indicator of level of service for all types of intersection control, a quantitative relation 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 relation is established, the maximum volume that can be accommodated at each level of service can be determined.

May and Pratt (9) used the results of simulation to correlate average delay with load factor for signalized intersections and thus linked average delay to level of service as described in the 1965 Highway Capacity Manual (HCM) (1). This relation is presented in an analysis by May and Pratt (9, Table 2, p. 47) that defines reasonable and orderly relations between average delay and level of service at signalized intersections. Recent observational work by Sutaria and Haynes (7, Figure 2, p. 111) adds support to this concept and defines quite similar break points for the various levels of service. The results of the work of May and Pratt and Sutaria and Haynes are given below:

Level of Service	Average Individual Delay (seconds per vehicle) May and Pratt	Sutaria and Haynes
A	≤15	≤12.6
B	≤30	≤30.1
C	≤45	≤47.7
D	≤60	≤65.2
E	>60	≤82.8

Since operational delays for a given level of service should be consistent regardless of the type of control at the intersection, these same values can be used to describe levels of service at unsignalized intersections also.

After making a large number of runs of the TEXAS model for a wide range of traffic demand at a four-lane by four-lane intersection controlled by stop signs on all approaches, a graph was drawn to show total intersection volume versus average queue delay (see Figure 1). Lines that represent average delay at signalized intersections for the various levels of service that are listed by May and Pratt (9, p. 47) and given in the table above have been superimposed on the graph and extended downward from their intercept with the data points to show the related service volume for each level of service. The volume of traffic accommodated at each level of service, or the service volume, can be judged to be reasonable and can be expected to result in the general flow conditions described in the HCM (1). The same type of orderliness in these parameters was found for other lane arrangements.

The MUTCD (8, p. 33) states that one condition that might warrant a multiway stop sign is an average delay of at least 30 s/vehicle during the maximum hour. Since an average delay of 30 s is the upper boundary suggested for level of service B (see the table above), this adds validity to the choice of 30 s as the boundary between levels of service B and C at which intersections normally operate acceptably.

Average queue delay can be used as a measure of level of service for all intersections; however, for uncontrolled and yield-sign-controlled intersections, a more convenient indicator of level of service might be the percentage of vehicles that are required to stop. It is easier to measure the percentage of vehicles stopped than to determine delay. For yield-sign-controlled intersections, another candidate indicator is the percentage of vehicles required to slow to less than 16 km/h (10 mph) since a commonly accepted warrant for that control is that it may be used if the approach speed exceeds 16 km/h.

These two performance indicators—percentage of vehicles required to stop and percentage of vehicles required to slow to less than 16 km/h—may also be related to level of service through simulation studies. To establish these relations, the TEXAS model was run to examine traffic behavior at representative yield-sign-controlled intersections that had various lane arrangements and operated under a wide range of traffic volumes. The average queue delay that resulted from different percentages of vehicles slowing to less than 16 km/h and the average queue delay that resulted from different percentages of vehicles being required to stop were obtained.

The data points in Figure 2 show the percentage of vehicles on yield-sign-controlled approaches that slowed to less than 16 km/h versus average queue delay. Figure 3 shows the percentage of vehicles on the yield-sign-controlled approaches that were required to stop versus average queue delay. In both figures, horizontal lines that define the various levels of service in terms of average queue delay according to May and Pratt (see the preceding table) are superimposed. Each of these lines is extended downward from its intercept with the data points to describe, respectively, the level of service as indicated by the percentage of vehicles on sign-controlled approaches that slowed to less than 16 km/h (10 mph) and the percentage of vehicles on the signed approaches that were required to stop. A summary is given in the table below of the relation among level of service, average queue delay, percentage of vehicles slowing to less than 16 km/h, and percentage of vehicles required to stop for yield-sign-controlled intersections of the two-lane by two-lane and four-lane by four-lane configuration (1 km = 0.62 mile):

Level of Service	Average Queue Delay (s)	Percentage of Vehicles on Yield-Sign-Controlled Approaches: Slowing to < 16 km/h	Required to Stop
A	<15	<60	<40
B	<30	<70	<60
C	<45	<80	<70
D	<60	<85	<75
E	>60	>85	>75

RECOMMENDED PERFORMANCE INDICATORS FOR UNSIGNALIZED INTERSECTIONS

Average queue delay is recommended as the best indicator of level of service for stop-sign-controlled intersections. Average queue delay can be measured in the field by appropriate survey techniques, it can be understood by the user, and it can be simulated by the TEXAS model. The relation between average queue delay and level of service that is applicable to signalized intersections is also recommended for stop-sign-controlled intersections (see the values of May and Pratt in the table on p. 37).

For yield-sign-controlled intersections, the percentages of vehicles on signed approaches that must slow to less than 16 km/h (10 mph) and those that must stop can be considered as good indicators of level of service. The percentage of vehicles that must slow to less than 16 km/h can be determined from simulation or can possibly be measured in the field by using time-lapse photography; this measure can also be understood by the user. In addition, it has been recognized as the basis of a warrant for yield-sign control of intersections. Suggested relations between the percentage of vehicles that slow to less than 16 km/h and the various levels of service are given in the table above. The percentage of vehicles on the signed approaches that must stop can be measured easily in the field, is easily understood by the user, and can be simulated by the TEXAS model. Suggested relations between the percentage of vehicles that must stop and levels of service are also given in the preceding table.

Table 1 is a summary tabulation of recommended performance indicators for various levels of service at each type of unsignalized intersection. The indicator for uncontrolled intersections is consistent with that for yield-sign-controlled intersections. Suggested values for signalized intersections taken from May and Pratt (9) are also included in Table 1.

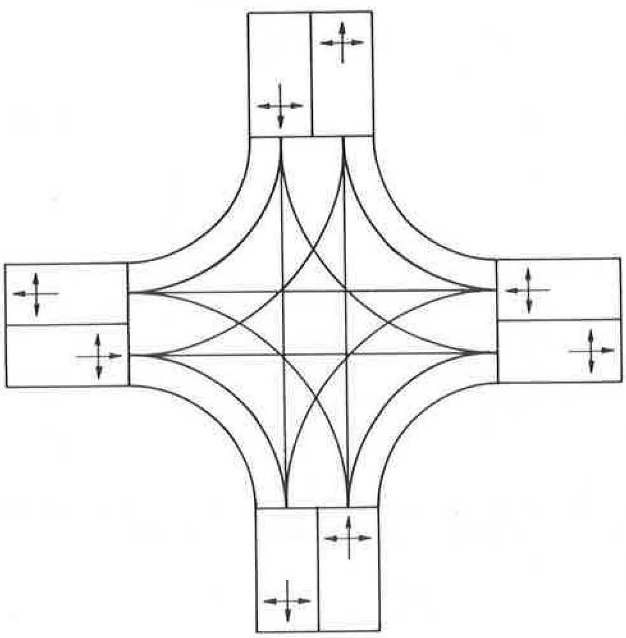
Table 1. Recommended indicators of intersection levels of service.

Type of Intersection Control	Recommended Performance Indicator	Level of Service A	B	C	D	E
Uncontrolled	Percentage of all vehicles that must stop	<40	<60	<70	<75	>75
Yield sign	Percentage of vehicles on sign-controlled approaches that must slow to 16 km/h	<60	<70	<80	<85	>85
	Percentage of vehicles on sign-controlled approaches that must stop	<40	<60	<70	<75	>75
Two-way stop	Average queue delay to vehicles on sign-controlled approaches (s)	<15	<30	<45	<60	>60
All-way stop	Average queue delay to vehicles on all approaches (s)	<15	<30	<45	<60	>60
Signal	Average stopped delay to vehicles on all approaches (s)	<15	<30	<45	<60	>60

Notes: 1 km = 0.62 mile.
Queue delay, the time spent by a vehicle while at a virtual stop in a queue on an intersection approach, is measured from the time the vehicle joins the queue until it enters the intersection and thus includes move-up time. Stopped delay, the time spent by a vehicle while it is actually stopped on an intersection approach, does not include move-up time.

Figure 4. Intersection used for cases 1, 2, and 3.

19TH ST AT CHICON
2-LANE MAJOR/2-LANE MINOR
242-m (800-ft) APPROACHES



SCALE FACTOR IS 1.8 m/cm (15 ft/in)

USE OF THE TEXAS MODEL IN CAPACITY ANALYSIS

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

1. Case 1—Lane configuration, type of control, and service volume accommodated are known; level of service is unknown. 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 level of service is then determined from Table 1.

2. Case 2—Lane configuration, type of control, and level of service are known; the service volume that can be accommodated is unknown. An estimate of the service volume is made. Then the 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 1. If this is not the level of service 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.

3. Case 3—Lane configuration and type of intersection control are known; the level of service provided for different volumes, or the maximum volume that can be accommodated at each level of service, is unknown. The 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 versus the specific indicator can be drawn, and, by using Table 1 as a guide, a table that links volume to level of service can be constructed and then used to determine the desired information.

4. Case 4—The service volume to be accommodated and the level of service to be provided are known; optimal design (lane configuration and control) is unknown. A lane configuration and a control scheme are chosen. Then the model is run with the desired volume and, from summary statistics and Table 1, 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.

EXAMPLE

To illustrate the use of the TEXAS model in the four cases described above, the following working example is presented. The items to be determined are (a) in case 1, the level of service at which a two-lane by two-lane uncontrolled intersection that accommodates 1600 vehicles/h will operate; (b) in case 2, the maximum volume that can be accommodated by a two-lane by two-lane uncontrolled intersection that operates at level of service B; (c) in case 3, the levels of service at different volumes and the maximum volume that can be accommodated at each level of service by a two-lane by two-lane uncontrolled intersection (analyzed by use of a graph and a table that will be constructed); and (d) in case 4, the optimum lane configuration and type of intersection control to accommodate 1600 vehicles/h while maintaining a level of service A.

Geometry of the Intersection

The intersection is assumed to be a right-angle 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 3 m (10 ft) wide. The influence of the intersection extends 242 m (800 ft) in advance of the intersection on each inbound lane and 121 m (400 ft) beyond the intersection on each outbound lane. The speed limit is 56 km/h (35 mph) on all approaches. There are no restrictions on sight distance. A plot of the intersection used for the example in cases 1, 2, and 3 is shown in Figure 4.

Traffic Data

1. The distribution of traffic on each approach is given below:

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

Table 2. Values supplied by the program for vehicle characteristics.

Vehicle Class	Vehicle Type	Length (m)	Operating Charac-teristic Factor	Maximum Deceleration (m/s^2)	Maximum Acceleration (m/s^2)	Maximum Velocity (m/s^2)	Minimum Turning Radius (m)	Aggressive Drivers (%)	Average Drivers (%)	Slow Drivers (%)	Percentage in Traffic Stream
1	Small automobile	4.57	100	4.88	2.44	45.73	6.1	30	40	30	20
2	Medium automobile	5.18	110	4.88	2.74	58.54	6.7	35	35	30	32
3	Large automobile	5.79	110	4.88	3.35	60.97	7.32	20	40	40	30
4	Van, minibus	7.62	100	4.88	2.44	45.73	8.54	25	50	25	15
5	Single unit	9.15	85	3.66	2.44	48.78	12.8	40	30	30	0.5
6	Semitrailer	15.24	80	3.66	2.13	48.78	12.19	50	40	10	0.2
7	Full trailer	16.77	75	3.66	1.83	45.73	13.72	50	40	10	0.1
8	Recreational	7.62	90	3.66	1.83	45.73	8.54	20	30	50	0.2
9	Bus	10.67	85	3.66	1.52	38.11	8.54	25	50	25	0.5
10	Sportscar	4.27	115	4.88	4.27	62.5	6.1	50	40	10	1.5

Figure 5. Example of summary statistics used in simulation.

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TEXAS TRAFFIC AND INTERSECTION SIMULATION PACKAGE - SIMULATION PROCESSOR
 *****       NSIM58U - 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 (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
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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 4).

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 40 km/h (25 mph) and the 85th percentile speed was 48 km/h (30 mph). On the major (east-west) approaches, the mean speed was 48 km/h and the 85th percentile speed was 56 km/h (35 mph).

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

6. Program-supplied values for the percentage of vehicles in each of 10 vehicle classes and the percentage of drivers in each of three driver classes were used (4, p. 33). Vehicle-related values are given in Table 2, and driver-related values are given below:

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

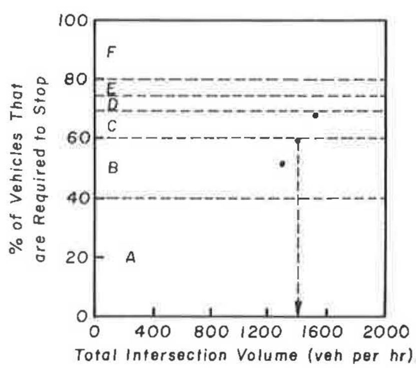

Figure 6. Service volume at level of service B for two-lane by two-lane uncontrolled intersection.

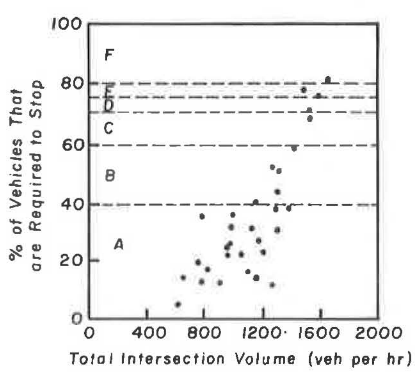

Figure 7. Analysis of two-lane by two-lane uncontrolled intersection.

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 0.5 s. Each unit was processed through the approach. Flow through the system was assumed to attain a steady-state condition in 2 min 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 min of real time. Figure 5 shows the summary statistics for the intersection used in this example. The intersection was uncontrolled in cases 1, 2, and 3; therefore, the total intersection volume and the percentage of vehicles that were required to stop were used for capacity analysis.

Analysis

Case 1

For a two-lane by two-lane uncontrolled intersection that accommodates a volume of 1600 vehicles/h, Figure 5 shows that the percentage of vehicles required to stop is 79.5 percent. From Table 1, the level of service provided is E.

Case 2

For a two-lane by two-lane uncontrolled intersection that is to operate at a level of service B, the first estimate of volume was 1300 vehicles/h. The percentage delayed in this case, after the model was run in the manner described above, was 51.7 percent. The level of service provided was B, but this is not the maximum volume that can be accommodated. The model was next run with a volume of 1500 vehicles/h. The proportion stopping was now 68.4 percent. The level of service provided in this case was C. Next the model was run with a volume of 1400 vehicles/h. The proportion of vehicles required to stop was now 59.3 percent, which is very close to the upper boundary of level of service B. Thus, it can be stated that the service volume of the two-lane by two-lane uncontrolled intersection operating under a level of service B is 1400 vehicles/h. Figure 6 shows a graph of total intersection volume versus the percentage of vehicles required to stop for these three runs.

Case 3

Analysis on a two-lane by two-lane uncontrolled intersection was conducted by running the TEXAS model with a wide range of volumes. From the summary statistics reported, a graph was drawn for total intersection volume versus the percentage of vehicles that are required to stop (see Figure 7). Horizontal lines that represent levels of service, obtained from Table 1, were superimposed, and a table that relates level of service to total intersection volume was constructed. This table, which is given below, can be used to find the level of service provided at any volume and the maximum volume that can be accommodated at

Table 3. Level of service for total intersection volume of 1600 vehicles/h.

Type of Traffic Control	Lane Configuration: Two-Lane Major, Two-Lane Minor	Two-Lane Major, Four-Lane Minor	Four-Lane Major, Two-Lane Minor	Four-Lane Major Four-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

each level of service for a two-lane by two-lane uncontrolled intersection:

Level of Service	Percentage of Vehicles Required to Stop	Intersection Service Volume (vehicles/h)
A	40	1200
B	60	1400
C	70	1500
D	75	1600
E	75	1600

Similar graphs and tables can be constructed for other traffic controls and lane arrangements.

Case 4

To design the intersection so that 1600 vehicles/h 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 vehicles/h until the desired level of service was attained. An efficient and economical way would be to try the most likely arrangement. For a first trial, a two-lane by two-lane stop-sign-controlled intersection was tried. A level of service D was provided, so a four-lane by four-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 A.

Table 3 gives a matrix of lane arrangements and control schemes that were run and shows the level of service that would be provided under each scheme. The table can be used in two ways: to determine the level of service of an existing or proposed intersection or to design an intersection to provide any desired level of service. The table is to be used when total intersection volume is 1600 vehicles/h, distributed according to the assumed traffic data given earlier. Similar tables can be constructed for different intersection volumes once the proper distribution is determined.

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The contents of this paper reflect our views, and we are responsible for the facts and the accuracy of the data presented. The contents do not necessarily reflect the official views or policies of FHWA. This report does not constitute a standard, specification, or regulation.

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Integrated System for Urban Traffic Data Collection

J. Uren, Portsmouth Polytechnic, Portsmouth, England
J.B. Garner, University of Leeds, Leeds, England

A technique developed at the University of Leeds that combines the collection, analysis, and presentation of data on urban traffic flow in one integrated system is described. Black-and-white aerial photographs of the central area of the city of Leeds were used. The analysis technique involves the use of a coordinate reader and a computer. Data on vehicles in motion and temporarily halted vehicles are collected on a street-by-street basis and fed into the computer on high-speed paper tape. These data are then used to calculate several major