Simulation of Two- and Four-Way Stop Control

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The development of digital computer simulation models representing vehicle interactions at highway intersections controlled by two- and four-way stop control is described. Driver actions at the stop lines are made on the basis of gap acceptance, and the appropriate distribution of gap acceptance may be selected on the basis of site experience. Demand flows on the approach highways may also be selected according to traffic flow conditions that vary from a uniform flow to a peak-hour flow with pronounced variation between maximum and minimum flow levels. Output from the simulation models is in the form of queue lengths and average and total delays. Observations of lag and gap acceptance and vehicle headway distributions are used in the simulation models to evaluate the relative advantages of two- and four-way stop control in terms of average delay. For the traffic flow conditions simulated, values of total practical intersection capacity occurred when the total inflow was approximately 1,400 veh/hr for a two-way stop intersection with one-lane approaches and 1,650 veh/hr for a four-way stop intersection with one-lane approaches.

When at-grade stop-controlled intersections are used, the capacity of a highway network is frequently limited by the capacity of the intersecting highways. For this reason, the capacity of, and delays at, at-grade intersections are of considerable interest to highway engineers.

The development of improved guidelines for the use of stop sign control at highway intersections was addressed by Upchurch (*1*), who selected as principal criterion for the evaluation of different control strategies the total cost of operation. Three types of control were analyzed: yield control, two-way stop control, and four-way stop control. The traffic experimental and analysis simulation (TEXAS) intersection simulation model was used to generate data on intersection operation for the calculation of vehicle operating and delay costs. Results indicated that for the accident rates used, yield control was the most economical type of control. Moreover, in most cases, two-way stop control was considered to be economically preferable to four-way stop control. However, for selected conditions of low volume or where minor-street volume was approximately equal to major-street volume, four-way stop control was found to be preferable.

Lee and Savur (*2*) had previously investigated intersection capacity and level of service (LOS) by using the TEXAS simulation model. Queue delay was used as a performance indicator and was recommended as the best indicator of LOS for stop-controlled intersections.

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DEVELOPED SIMULATION MODELS

It was decided to use a simulation approach to investigate the relative advantages of two- and four-way stop control. Regular time scanning was adopted in the simulation models that were developed, the selection of the appropriate scanning interval depending on the level of accuracy required and on the available computer resources. From these considerations, a scanning interval of 0.5 sec was adopted. The performance indicators used were

1. Maximum and average queue length,
2. Total queuing delay to all vehicles, and
3. Average queuing delay to all vehicles.

The main models developed in this study were

1. Model TWSSIM: This model was developed to depict vehicular interactions at crossroad intersections controlled by a two-way stop (major-minor) priority rule.
2. Model FWSSIM: This model was developed to simulate the performance of a crossroad intersection controlled by a four-way stop (off-side) priority rule.

The main simulation models, together with the other necessary submodels, were built into a general and modular computer program, SIMPHINT. The details of the programming aspects are discussed by Ismail (*3*). Figure 1 shows an outline layout of the system. In general, the system was divided into three basic components: the main simulation models, the vehicle-driver submodels, and the computation submodels. The main simulation models described the movements of the different streams within the intersection area under the given priority rules and geometric layouts. The vehicle-driver submodels provided the required input values for the main simulation models. These input values, such as the critical acceptable lags and gaps, the time headways between vehicles, and the assignment of turning movements, are generated using the appropriate predefined distributions. The computation submodels carry out the necessary calculations required to update the values and compute the results summary during the simulation run.

THE GAP ACCEPTANCE SUBMODEL

Both types of priority rules considered depended mainly on the concept of gap acceptance, which has been extensively studied in the United Kingdom for two-way stop intersections

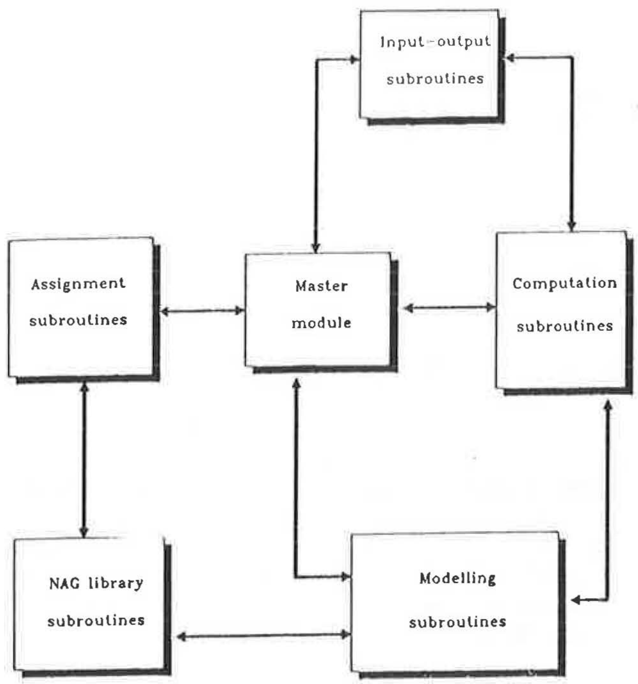

FIGURE 1 The general conceptual approach.

but not for four-way stop intersections. Vehicles arriving at the junction from controlled approaches are obliged to give way to vehicles on the controlling approaches. Four options for the acceptance distribution were included in the model:

1. A step function,
2. A cumulative normal distribution,
3. A cumulative log-normal distribution, and
4. A linear distribution.

Drivers are considered to be consistent in their decision to accept, or reject, the available gaps, i.e., the critical acceptable gap value assigned to the waiting driver remains unchanged until an available gap is accepted. In generating the critical acceptable values, the three different turning movements—left turn, straight ahead, and right turn (U.S. rules of the road)—are treated separately, because it is most likely that drivers' behavior in executing different turning movements is not unique. Different acceptance distributions may also be specified in the input data for the different intersection approaches. In assigning the critical acceptable values to each driver there are three possibilities, selection of which depends on the level of available data:

1. When detailed data are available to the traffic engineer, the waiting driver is first assigned a critical acceptable value from either a delayed gap or undelayed lag acceptance distribution, according to the vehicle's position in the queue. A delayed lag acceptance distribution is used for vehicles that arrive at the junction when a queue exists, whereas an undelayed lag acceptance distribution is used for vehicles arriving at the stop line when a queue does not exist. In the latter case, if the available lag is accepted, no further assignment is needed, whereas if that lag is rejected, then a critical acceptable gap is assigned for the waiting driver from the appropriate delayed gap acceptance distribution.
2. When less detailed data are available, no distinction is made between delayed and undelayed vehicles lags. Values of critical acceptable lags or gaps are assigned to waiting drivers regardless of whether they had joined the queue or arrived directly at the stop line. A critical acceptable gap is assigned to a waiting driver if the available lag is rejected.
3. A rather coarser approach in which each waiting driver is assigned a single value from a lag-and-gap acceptance distribution. This value is considered to represent the driver's critical acceptable value with which the available lag, and the subsequent available gaps, may be compared.

FLOW PATTERN SUBMODEL

The modeling of the flow pattern or profile throughout the simulation period is one of the factors that affects the realism of any simulation model. Generally, traffic flow varies considerably with time throughout the day and this variation is more pronounced during peak periods. Therefore, a demand flow profile that varies with time provides a more realistic and more accurate base for the calculation of queue length and delay at highway intersections. In the system developed, three options were considered to model the demand flow profile on the intersection approaches. In the first option, demand flow values, for each approach, can be input directly at specified time intervals. In the second option, it is only necessary to input three flow values to represent the peak period under consideration. These are prepeak, peak, and postpeak flow values. Three values on the time scale are also necessary; these are the time at which the flow starts to increase to the peak flow, the time of the peak flow, and the time at which the flow starts to decay to the postpeak flow. These flow and time values are used by the model to synthesize, from a normal distribution, the flow profile over the simulated period. The third option is to provide only the average demand flow value, for the whole simulation period, which will be used to synthesize the flow profile from a normal distribution using default values embedded in the model.

ASSUMPTIONS AND MODEL FRAMEWORKS

The general rules considered in the formulation of the simulation models in this study were as follows:

1. The headway distributions on the approaches to the intersection are represented by the displaced negative exponential distribution.
2. Drivers on the controlled streams, i.e., those who are waiting for an acceptable lag (or gap) in the controlling streams at two-way stop intersections, are assumed to be homogeneous and consistent in their responses to the available lags (or gaps) in those streams.
3. Vehicles arriving at the intersection in the controlled streams are put in a queue in the appropriate queuing lane according to the direction of movement and the layout of the approach.
4. No vehicle can enter the interaction zone while it is occupied by another vehicle, except for compatible movements.

5. Vehicles from the controlled stream can enter the intersection area if, and only if, an acceptable gap exists in all the controlling streams simultaneously.

6. The decision of direction of movement is assigned randomly to each vehicle arriving at the intersection on a given approach according to predefined turning proportions for that approach.

7. Drivers turning right (U.S. rules of the road) from the near-side controlling stream indicate their direction of movement at a suitable time prior to their arrival at the intersection, so that drivers on the controlled streams are able to consider the next available lag (or gap) on that controlling stream.

8. Parking is prohibited in the vicinity of the intersection area.

9. Overtaking is not allowed within the intersection area.

10. Interference between vehicles and pedestrians in the intersection area is not considered.

11. Queuing delay was only derived from the models.

12. All approaches to the intersection were considered to be subject to a 30-mph speed limit.

PARAMETRIC ANALYSES

The practical use of the simulation model can be demonstrated by performing a range of parametric analyses. This task may be accomplished by subjecting the validated model to hypothetical sets of input parameters, and by studying the effect of these parameters on the performance of the model. The analysis was mainly concentrated in two areas, type of intersection control and intersection geometry. In summary, more than 700 hr of vehicular interactions were simulated using the developed simulation program SIMPHINT, each simulation run representing 1 hr of real time.

EFFECT OF INTERSECTION CONTROL

Highway traffic engineers frequently face the problem of choosing the optimum type of control to be adopted at a particular intersection. At priority controlled intersections, the decision to use a certain priority rule or to change from one rule to another must be made according to guidelines on the basis of a specified criterion. The average delay per vehicle is widely accepted as such a criterion.

A series of simulation runs was made, and the required delay values were obtained from simulation model TWSSIM for an intersection with one-lane approaches under two-way stop control. These results are shown in Figure 2 over a range of input flow data. An average delay value of 60 sec, to all vehicles, was selected as a criterion to obtain the practical capacity of the intersection. Figure 2 shows that, at this delay value, the practical capacity of the intersection occurs when the total inflow is approximately 1,400 veh/hr over the range of minor-road flows shown.

Gap and lag acceptance is a critical phenomenon in the interaction between vehicles at priority highway intersections. During the validation of the simulation models, it was found that there were some differences between delayed and undelayed acceptance distributions. However, these differences were, in some cases, marginal. In order to investigate the effect of this factor, a series of simulation runs was made. In these runs, lag acceptance data were split into delayed and undelayed acceptance distributions. It was found that the effect was marginal without any significant difference in delay being observed, although it was expected that the difference could increase with an increase in total intersection flow. Nevertheless, in the light of more significantly different acceptance distributions, a different conclusion might be drawn.

The other form of intersection control that was of interest in this study was the four-way stop priority rule. In this priority rule, all the approaches to the intersection area are controlled by stop signs. Drivers approaching the intersection on a given approach are obliged to give way to those arriving from the left (U.S. rules of the road). In order to study the performance of highway intersections controlled by a four-way stop priority rule, the simulation model FWSSIM was used to obtain simulated delay values at hypothetical one-lane approach intersections controlled by a restricted four-way stop priority rule. Flow levels on the two intersecting roads were varied from 100 to 800 veh/hr in each direction, in increments of 50 veh/hr, to cover a wide range of traffic conditions. The turning proportions assumed were 15, 70, and 15 percent for left-turning, straight-ahead, and right-turning movements (U.S. rules of the road), respectively.

The variation of average delay with major-road flow, for different minor-road flow levels, was used to study the intersection performance. Figure 3 shows that for a range of flow values the average delay increases with an increase in major road flow. In order to obtain the practical capacity of the intersection under this priority rule, i.e., four-way stop, the same average delay criterion of 60 sec to all vehicles was selected. It was concluded that the practical capacity of the intersection under this type of control occurs when the total inflow is about 1,650 veh/hr.

COMPARISON BETWEEN TWO- AND FOUR-WAY STOP CONTROL

In order to obtain practical warrants that can be implemented by practising highway traffic engineers, four-way stop priority control was compared with two-way stop control under the same traffic and geometric conditions. Generally, at high flow levels, two-way stop control tends to cause higher average delays to those vehicles that are delayed on the minor road than four-way stop control, especially when the two intersecting roads have approximately equal traffic flows. Under these conditions, a four-way stop priority rule provides a better distribution of delays between the two intersecting roads. For this reason, when based on average delay, the practical capacity of the intersection (on the basis of observed U.K. gap acceptance) obtained from applying a four-way stop priority rule (1,650 veh/hr), as shown on Figure 3, was higher than that obtained from using a two-way stop priority rule (1,400 veh/hr), as shown on Figure 2, for the same traffic and geometric conditions.

A series of simulation runs was carried out with left-, straight-ahead and right-turning movements (U.S. rules of the road) in the proportions of 15, 70, and 15 percent, respectively, for two- and four-way stop control with single-lane approaches. For each simulation run, the flows on the four approaches

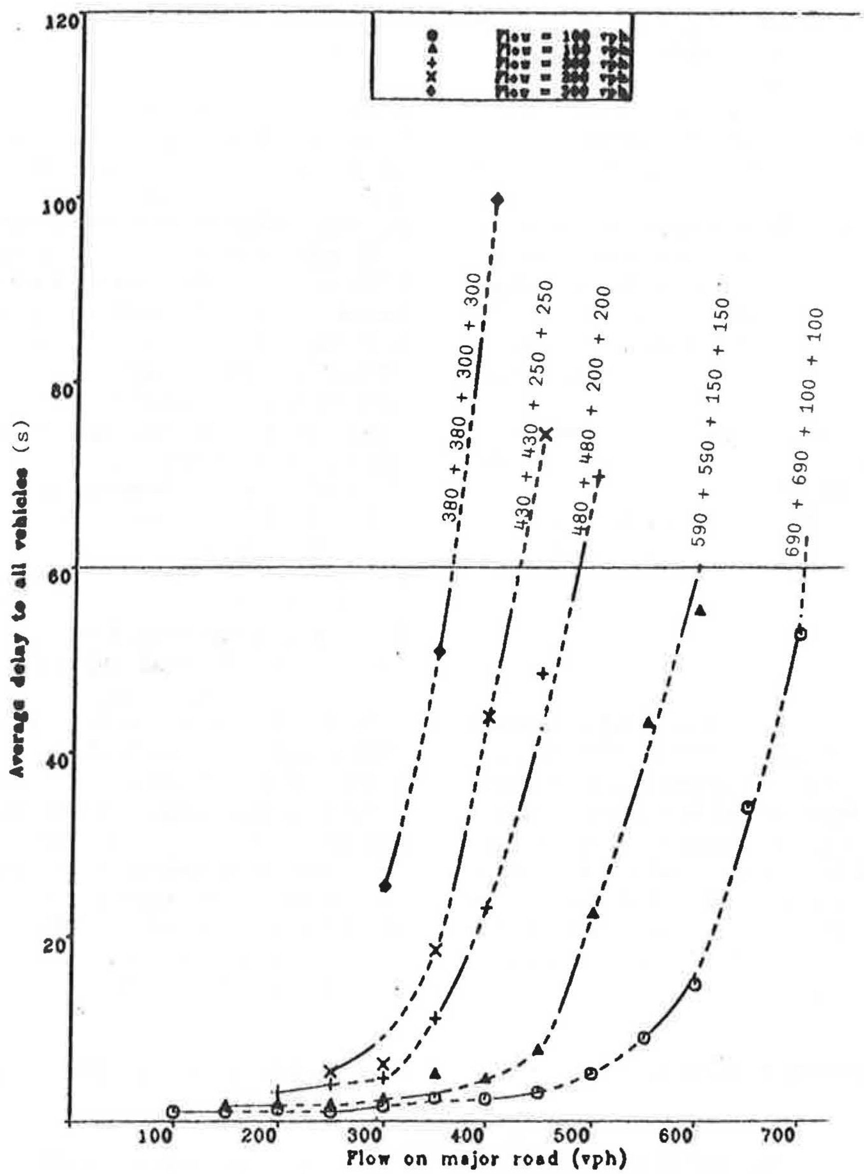

FIGURE 2 Flow-delay relationships at two-way stop priority highway intersections for one-lane approaches with flows for each approach (minor road flow, 100 to 300 vph).

were equal. Values of average delay obtained from the simulations are presented in Table 1.

These values indicate, for the flow conditions simulated, that at low flow levels there is no significant difference between the two control methods, whereas, at flow levels exceeding 250 veh/hr per approach, the use of a four-way stop priority rule yields lower delay values than the use of a two-way stop priority rule. This conclusion is justified in terms of both delay distributions and overall average intersection delay.

EFFECT OF INTERSECTION GEOMETRY

The geometrical layout of the intersection area has a considerable influence on intersection performance. Generally, the adoption of better design standards will be reflected in enhanced intersection performance. However, the strategy adopted in the design of a given intersection is a function not only of road users' convenience, but also of the space available, and the resources allocated for that intersection. The effect of the number of lanes on the intersection approaches is described under the two methods of control. The purpose of the analysis was to establish some guidelines regarding the adoption of a suitable layout at highway intersections. The number of queuing lanes provided on the controlled approaches to the intersection area is one of the factors that assist in providing improved performance. This improvement is achieved through the reduction of queuing delay on these approaches by increasing the service channels available, and hence increasing the opportunities for vehicle release.

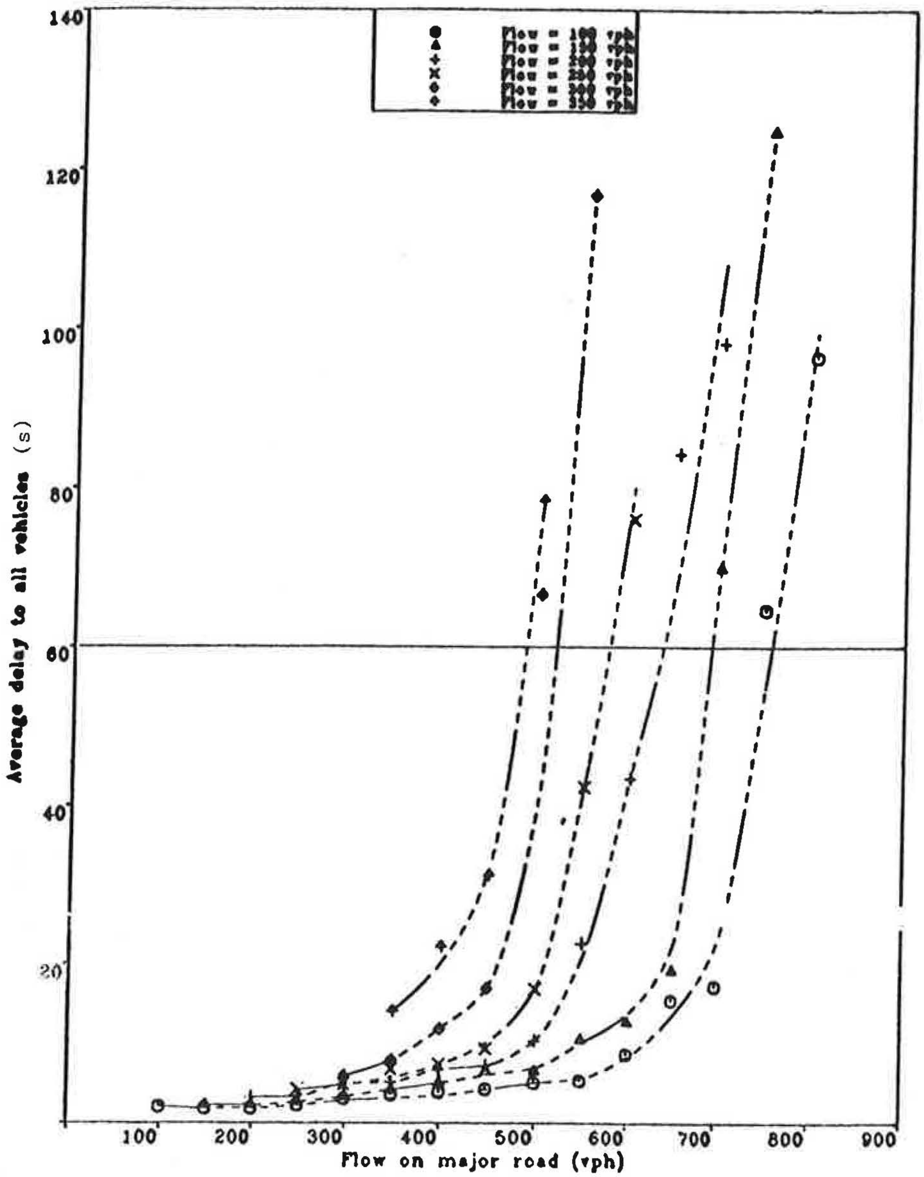

FIGURE 3 Flow-delay relationships at four-way stop priority highway intersections for one-lane approaches with flows for each approach (minor road flow, 100 to 350 vph).

In order to study the effect of this factor on highway intersections controlled by a two-way stop priority rule, the simulation model TWSSIM was used to generate a range of delay values for two different layouts. In the first, a one-lane major road intersects a one-lane minor road, whereas in the second, each of the two intersecting roads has a two-lane approach. In order to use these results to obtain guidelines for the provision of one or two approach lanes at intersections controlled by a two-way stop priority rule, certain criteria were defined. Using a 60-sec average delay as this criterion, average delay contours were derived as shown in Figure 4. This figure can be accessed with a combination of flow levels on the major and minor roads to select a suitable layout using delay criteria.

Similarly, the simulation model FWSSIM was used to study the effect of the number of approach lanes on the performance of intersections controlled by a four-way stop priority rule. Two cases were again considered in the analysis, one- and two-lane approaches. Using the same average delay criterion of 60 sec, guidelines were derived for the selection of the appropriate layout for intersections controlled by four-way stop intersections. The 60-sec average delay contours for the two layouts are shown in Figure 5 and can be used to choose the appropriate layout for a given combination of major- and minor-road flow levels.

CONCLUSIONS

The main conclusions that were drawn from the simulation study of two- and four-way stop control are as follows:

TABLE 1 COMPARISONS OF AVERAGE DELAY AT AN INTERSECTION OPERATING UNDER TWO- AND FOUR-WAY STOP CONTROLS

Flow on each approach (vph/approach)	Average delay to all vehicles (s)	
	two-way stop	four-way stop
100	1.1	2.0
150	1.6	2.2
200	3.1	3.2
250	5.3	4.2
300	25.5	5.9
350	*	14.0
400	*	30.3

* long queues on the minor road approaches

1. Field observations at the validation site indicated that the shifted negative exponential represented the appropriate headway distribution for both stop and nonstop conditions.

2. The analysis of lag-gap acceptance observations indicated that there was a marked difference between acceptance distributions for the different turning movements at the given intersection approach. Average acceptable lag values on the minor-road approaches of the validation site controlled by a two-way stop priority rule were found to be 5.5, 5.5, and 4.5 sec for left-turning, straight-ahead, and right-turning movements (U.S. rules of the road), respectively. On the other hand, average acceptable gap values for the three directions of movements on these approaches were 6.0, 4.85, and 4.75 sec, respectively.

3. A detailed analysis of lag-gap acceptance data was carried out where lags were split into two categories, delayed and undelayed, according to the queuing condition at the time of arrival of the vehicle. However, marginal differences were found between observed delayed and undelayed lag acceptance distributions for the different turning movements.

4. Theoretical distributions were fitted to the observed acceptance distributions in the form of normal, log-normal, and linear functions. The appropriate distribution was then se-

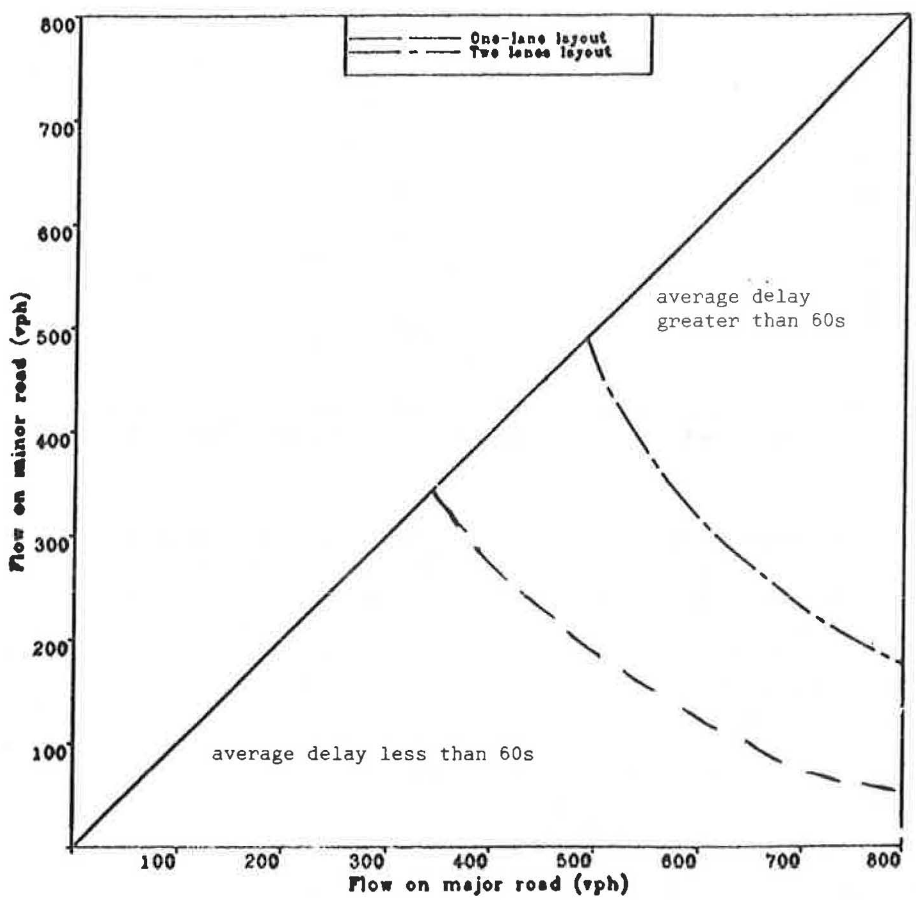

FIGURE 4 Average delay contours at two-way stop priority intersections with different geometric layouts for all one-way flows.

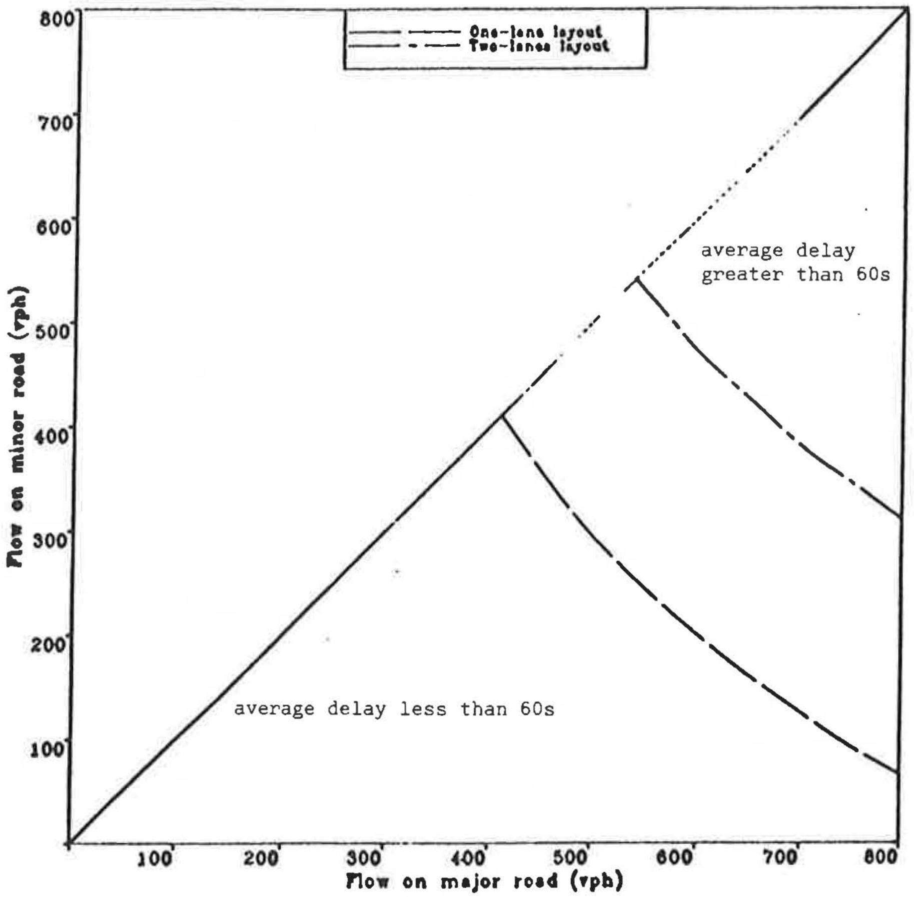

FIGURE 5 Average delay contours at four-way stop priority highway intersections with different geometric layouts for all one-way flows.

lected for each combination of intersection approach and lag-gap category and used in the validation of the developed simulation models. Simulated queue lengths and delay values obtained from the models were compared to the observed values, and good agreement was found.

5. At two-way stop priority highway intersections, the average delay per vehicle increased nonlinearly with the increase in flow levels. Using a selected delay criterion of 60 sec average delay to all vehicles, the practical capacity of the intersection with one-lane approaches occurred when the total inflow was approximately 1,400 veh/hr.

6. The effect on delay of using the detailed lag-gap acceptance categories, delayed lags, undelayed lags, and gaps, was found to be marginal. It is believed that this marginal effect is caused by the relatively small difference between the two lag categories observed at the validation site.

7. At four-way stop priority highway intersections, the average delay per vehicle was found to increase with the increase in flow levels in a nonlinear form. The practical capacity of one-lane approach intersection controlled by this priority rule was determined according to the same delay criterion of 60 sec average delay to all vehicles and occurred when the total inflow was approximately 1,650 veh/hr.

8. At equal flow levels and for the turning movements input on the major and minor roads, four-way stop control provided a more even distribution of delay than two-way stop control, and reduced queue lengths on the minor-road approaches. The overall intersection delay experienced under these conditions was found to be lower in the case of the four-way stop than the two-way stop for flows exceeding 250 veh/hr on each approach. Therefore, it is concluded that for equal flows and specified turning movements on each approach above this critical level, four-way stop rule provides a better control method than two-way stop control.

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