

Microscopic Simulation Modeling of Minimum Thresholds Warranting Intersection Signalization

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The subject of this paper is use of a microscopic simulation model to estimate the minimum thresholds that require the installation of traffic signals at intersections. A simulation modeling approach was used to evaluate the reasonableness of signal installation Warrants 1 and 2 documented in the *Manual on Uniform Traffic Control Devices* (MUTCD). The results obtained from the simulation experiment indicate that the MUTCD warrants are conservative for some situations and hence if rigidly applied can result in premature installation of traffic signals. It was deduced from the simulation experiment that the minimum thresholds that require the installation of traffic signals depend on the geometric configuration of the intersection, that is, four-leg versus T-intersections. For example, according to the results obtained from the simulation experiment, for the same traffic conditions, four-leg intersections will require lower thresholds than T-intersections. A reasonable minimum threshold was estimated for T-intersections. This threshold can be used to supplement the MUTCD warrants.

The *Manual on Uniform Traffic Control Devices* (MUTCD) is considered the authoritative reference manual for implementing a number of traffic control measures, including the warrants for traffic signal installation at intersections. Usually a traffic condition satisfying one or more of the warrants documented in the MUTCD is considered necessary for traffic signal installation. These warrants include minimum traffic volumes on the major and the minor streets.

Typical thresholds used range from 500 to 900 vehicles per hour (vph) for the major streets and a one-way volume of 75 to 200 vph for the minor streets (1). In addition, some states and localities have additional sets of guidelines to supplement those of the MUTCD.

Traffic signals have proven to be very effective in improving safety and traffic flow at intersections. However, experience has shown that traffic signals can be a nuisance if not properly timed or if used when not "warranted," or both. For example, poorly timed signals impede the flow of traffic by giving green time to approaches that do not have adequate demand. This type of problem is more prevalent at isolated intersections with pretimed traffic signals.

In order to minimize the likelihood of premature installation of traffic signals at intersections, it is very important to evaluate and validate commonly used guidelines (i.e., guidelines documented in the MUTCD).

For this paper, a microscopic simulation modeling approach is used to evaluate the minimum thresholds (traffic volumes) documented in the MUTCD that warrant traffic signal installation. A set of supplementary guidelines that could be used in conjunction with those of the MUTCD is suggested.

BACKGROUND OF THE PROBLEM

Historically, minimum vehicular volumes warranting traffic signal installation are generally applied to all intersections with little consideration to the geometric configuration of the intersection (1).

As documented in the 1985 *Highway Capacity Manual* (HCM) (2), traffic for the different lane-groups accepts different safe gaps to undertake turning maneuvers. For example, minor-street left-turning traffic accepts significantly larger gaps than minor-street right-turning traffic, and so on. Consequently, two intersections with the same total major- and minor-street traffic volumes may not operate at the same level of service (LOS). The intersection with the most vehicular movement conflicts is expected to operate at a lower LOS than the intersection with the least vehicular movement conflicts. Therefore, the geometric configuration of the intersection is a very important factor to consider in estimating the thresholds warranting signal installation. For example, T-intersections have fewer vehicular movement conflicts than do four-leg intersections. Consequently, it will be unreasonable to apply the same minimum thresholds to these two categories of intersections.

OBJECTIVES

The objectives of this paper are to evaluate, via simulation, the minimum thresholds warranting traffic signal installation as documented in the MUTCD and to provide supplemental guidelines.

ASSUMPTIONS

The building of the simulation model involved several assumptions, most of which are based on standard traffic engineering practices. The assumptions made are discussed under five major categories: (a) geometric configuration of the intersection used, (b) service prioritization of the different lane-

group traffic movements at the intersection, (c) traffic flow parameters used in the simulation experiment, (d) configuration of the simulation model, and (e) decision rules for the simulation experiment.

Geometric Configuration of the Intersection

The minimum thresholds warranting traffic signal installation depend on the configuration of the intersection. One of the primary purposes of traffic signals is to minimize vehicular conflicts at intersections. The severity of the conflicts depends on the number of different types of turning maneuvers at the intersection. For example, intersections of two-way streets have more vehicular conflicts than those of one-way streets, and four-leg intersections have more vehicular conflicts than T-intersections. Clearly, each of the above two cases of intersections requires a different set of minimum thresholds warranting traffic signal installation.

In the simulation experiment, two sets of intersections were considered. These were a four-leg intersection with two-way major- and minor-street traffic and a T-intersection with two-way major- and minor-street traffic.

Prioritization of Traffic Movement

Using the 1985 HCM (2) guidelines for "unsignalized intersection analysis," turning movement priorities were established (see Figure 1). Because both the major-street through movements and right-turn movements are usually unimpeded, these movements were designated Priority 1, the major-street left-turn movements Priority 2, the minor-street right-turn movements Priority 3, the minor-street through movements Priority 4, and the minor-street left-turn movements Priority 5. Priority 1 has the highest preference and Priority 5 has the lowest preference with regard to service.

Traffic Flow Parameters

As mentioned earlier, major-street through and right-turn traffic at unsignalized intersections is usually unimpeded. Lower-priority traffic movements will have to queue whenever there is major-street through or right-turn traffic, or both, at the intersection.

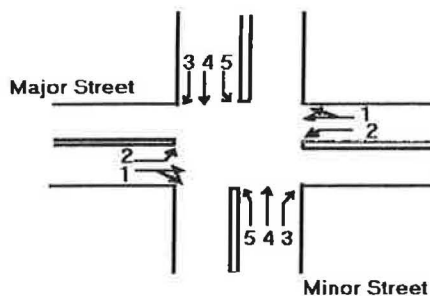


FIGURE 1 Movement categorization.

The service time—that is, the time taken by a vehicle to traverse the intersection—depends on two major variables: the width of the intersection and the average travel speed of the vehicle. Therefore, in the simulation experiment, exponentially distributed service times were assumed for all lane-groups (i.e., Lane-Groups 1, 2, 3, 4, and 5). Using the critical gap acceptance data documented in the "unsignalized intersection analysis" section of the 1985 HCM, average service times (Table 1) were assumed of 2, 5, 5.5, 6.5, and 7.0 sec/vehicle for Lane-Groups (movement priorities) 1, 2, 3, 4, and 5, respectively (2).

In the simulation experiment, vehicles were served one at a time on the basis of the aforementioned service priorities. However, in the real world, more than one vehicle can be served at a time. This is particularly true for traffic belonging to the Priority 1 lane-group category. For example, although arrival and departure at unsignalized intersections are generally considered random, vehicles belonging to the major-street through and right-turn lane-group category can arrive and be served from both directions at the same time. Therefore, the minimum threshold estimated from the experiment could be even less than the "actual" threshold.

A Poisson traffic arrival pattern, that is, exponentially distributed interarrival times, was used. The vehicular arrival rate, A_i , at the intersection was estimated as

$$A_i = (\sum v_i)/3,600 \quad (1)$$

where A_i is the average traffic arrival rate (in vehicles/second) at the intersection and v_i is the traffic volume at the intersection for lane-group i (in vehicles/hour).

In the simulation experiment, the expected traffic arrival rate (i.e., demand for a given lane-group) was estimated as

$$A_i = A_i(P_i) \quad (2)$$

where A_i is the expected traffic arrival rate for Lane-Group i and P_i is the probability that a given arrival at the intersection belongs to Lane-Group i ; that is, $P_i = v_i/\sum(v_i)$.

As mentioned earlier, the interarrival times at the intersection are assumed to be exponentially distributed. Thus, the parameter of the exponential distribution is $1/A_i$.

Decision Rules

As mentioned earlier, one of the primary purposes of traffic signals is to reduce vehicular conflicts and hence to increase traffic flow at intersections. Without traffic signals, arrivals other than those belonging to the Priority 1 lane-group category would have to remain in the queue until a safe gap was available to undertake turning maneuvers. As the traffic on the major street or on the minor street, or both, increases, the likelihood of finding safe gaps for turning maneuvers reduces. Eventually, the expected available number of safe gaps will become less than the expected number of vehicles to be served.

This study assumes the minimum demand thresholds that warrant the installation of traffic signals at an intersection to

TABLE 1 Lane-Group Service Times

Critical Lane-Group	Average Service Time per Vehicle
1. Major Street Through & Right-turn	2.00 seconds
2. Major Street Left-turn	5.00 seconds
3. Minor Street Right-turn	5.50 seconds
4. Minor Street Through	6.50 seconds
5. Minor Street Left-turn	7.00 seconds

be the thresholds beyond which queues on one or more lane-groups at the intersection will no longer attain statistical equilibrium. In other words, the queue or queues will continue to increase with time as the expected demand exceeds the expected available safe gaps required to undertake turning maneuvers. Figure 2 shows when traffic signal installation is necessary. It can be seen that the queues for movements (MVTs) 1 and 2 are statistically stable, whereas the queue for MVT 5 increases with time. In other words, the queue for MVT 5 cannot attain statistical equilibrium, a condition warranting traffic signal installation.

CONFIGURATION OF THE SIMULATION MODEL

The SIMAN simulation package was used in building the model. Figure 3 shows the architecture of the simulation model, which contains four main blocks: vehicular arrival block, lane-

group categorization block, service block, and queue inventory block.

Vehicular Arrival Block

The purpose of the vehicular arrival block is to create the traffic arriving at the intersection. Arrivals created in this block are considered generic. They do not have any lane-group identifications.

Lane-Group Categorization Block

The arrivals created are brought into the lane-group categorization block, where they are categorized and assigned to the appropriate lane-groups. Assignments are made on the basis of the aforementioned probability, P_i , assigned to the individual lane-groups at the intersection.

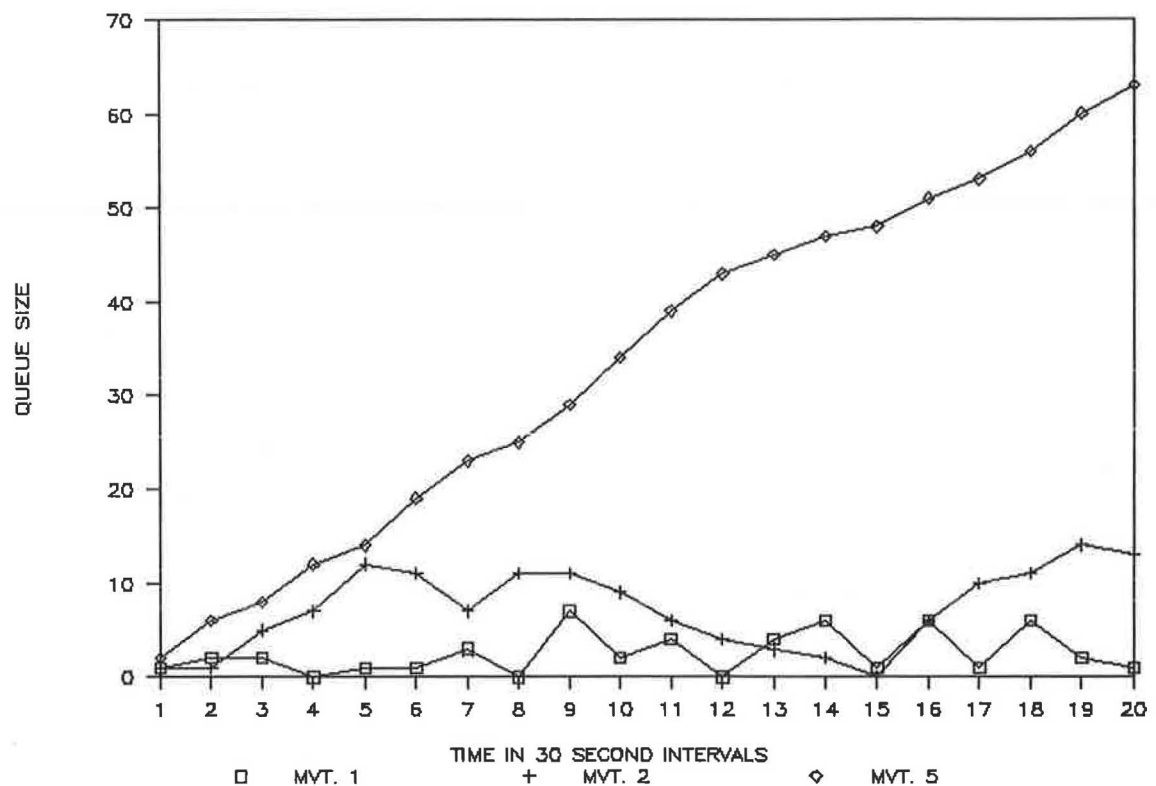


FIGURE 2 Minimum threshold requirements.

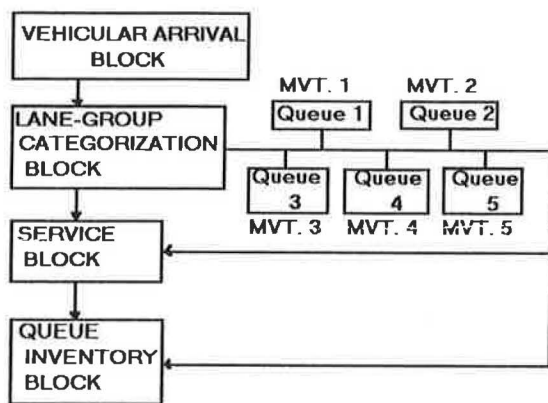


FIGURE 3 Configuration of simulation model.

Vehicular Service Block

Vehicles assigned to a given lane-group are either served or sent to a queue block. Services are rendered in accordance with the aforementioned lane-group service prioritization.

Queue Inventory Block

Unserved vehicles for a given lane-group are stored in the queue block reserved for that lane-group. The size of the queue for the individual lane-groups is continually updated in the queue inventory block. In addition, the queue size is reported at 30-sec intervals for a minimum observation period of 20 min or 600 sec. The status of the queue for the individual lane-groups during the period of observation was evaluated from output graphs. In other words, the graphs were used to easily identify lane-groups where queues do not attain statistical equilibrium. As mentioned earlier, the stability of the queues at the intersection is used as a guide to determine whether traffic signal installation is necessary.

DESCRIPTION OF THE EXPERIMENT

As stated earlier, the primary objective of this study is to evaluate the suitability of the MUTCD "minimum volumes warrants for traffic signal installation" for both four-leg and T-intersections. The study considered two cases, Scenarios 1 and 2. Scenario 1 involves the evaluation of the performance of the aforementioned MUTCD warrants for four-leg inter-

sections and Scenario 2 those for T-intersections. The MUTCD warrants evaluated in the experiment are the minimum volumes for intersections with two or more traffic lanes for both the major and minor streets.

The experiment began by inputting into the simulation model the equivalent traffic flow parameters of the MUTCD "minimum thresholds." The resulting queue and delay data were evaluated for statistical equilibrium for Scenarios 1 and 2. Using an increment of 50 vehicles at a time, a sensitivity analysis was undertaken to determine whether thresholds higher than those of the MUTCD would result in stable traffic conditions at the intersection. The term "stable" refers to the status of the queues at the intersections. As mentioned earlier, the decision rule of the experiment is that traffic signal installation is necessary when queues in one or more lane-groups cannot attain statistical equilibrium (see Figure 2).

SUMMARY OF RESULTS

Table 2 shows the minimum thresholds obtained from the simulation experiment for the aforementioned scenarios (see also Figures 4–6).

Figure 4 shows the behavior of the queues at a four-leg intersection when the aforementioned MUTCD warrants were applied. It can be deduced from Figure 4 that queues for MVT 2 attained statistical equilibrium, whereas those for MVTs 3 and 5 did not attain statistical equilibrium. Therefore, according to the aforementioned decision rule, traffic signal installation is necessary. Using threshold values slightly lower than those of the MUTCD resulted in satisfactory traffic conditions for MVTs 3 and 5. Therefore, it was concluded that the MUTCD Warrants 1 and 2 traffic signal thresholds are optimum for four-leg intersections.

Figure 5 graphs the behavior of the queues at a T-intersection when the aforementioned MUTCD Warrant 1 threshold was applied. It can be deduced from Figure 3 that even the queues for the most "critical" lane-group, MVT 5 (minor-street left-turn movement), were determined to be statistically stable when MUTCD Warrant 1 was applied to a T-intersection. Similar results were obtained for MUTCD Warrant 2 and slightly higher thresholds. This implies that the current MUTCD signal Warrants 1 and 2 are not "optimum" for T-intersections.

A sensitivity analysis was undertaken to estimate a more reasonable minimum threshold for T-intersections. Figure 6 shows the queue behavior for MVT 5 based on the estimated minimum threshold. It can be deduced from Figure 6 that the

TABLE 2 Estimated Minimum Thresholds

Intersection Geometric Configuration	Major Street two-way hourly volumes	Minor Street one-way hourly volumes
Four-Leg Intersection	600 vph	200 vph
	900 vph	100 vph
T-Intersection	1,000 vph	200 vph

MUTCD Warrants 1 & 2 minimum thresholds range from 500 to 600 vph and 750 to 900 vph (both directions) for the major street, and 150 to 200 vph and 75 to 100 vph (one direction) for the minor street, respectively. There are no separate guidelines for Four-leg intersections and T-intersections.

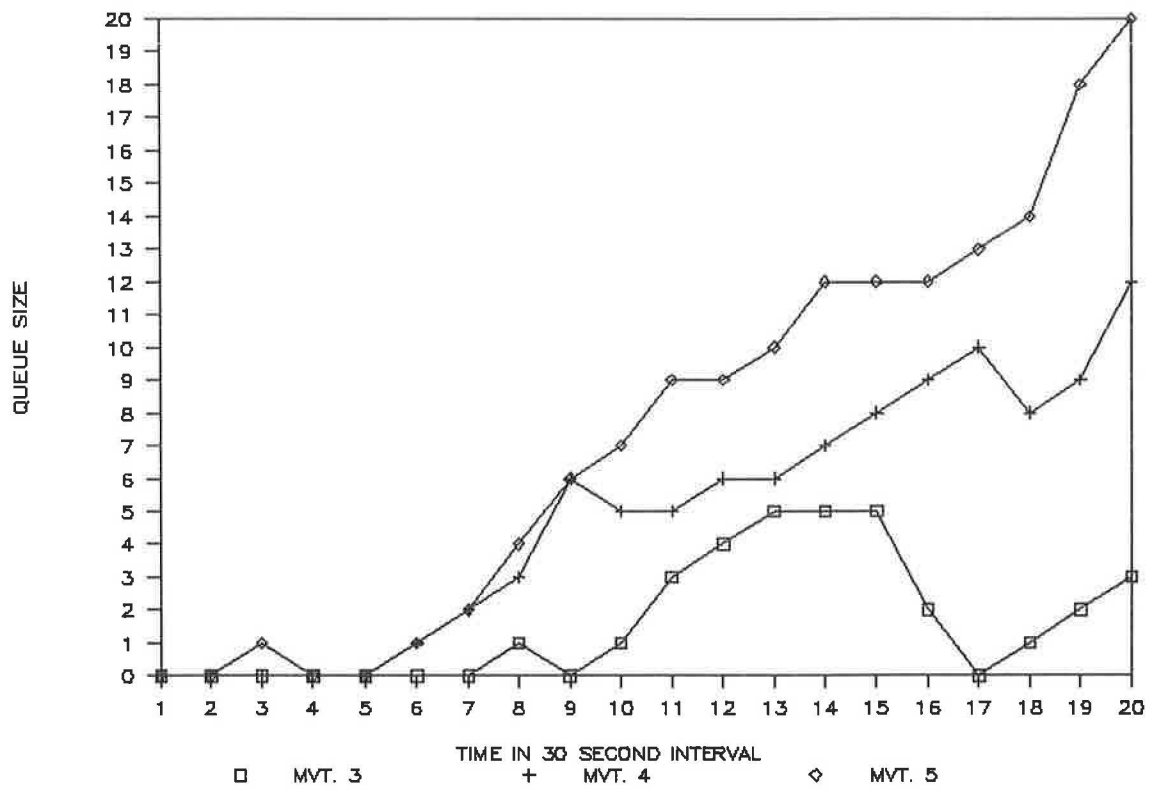


FIGURE 4 Queues for Scenario 1.

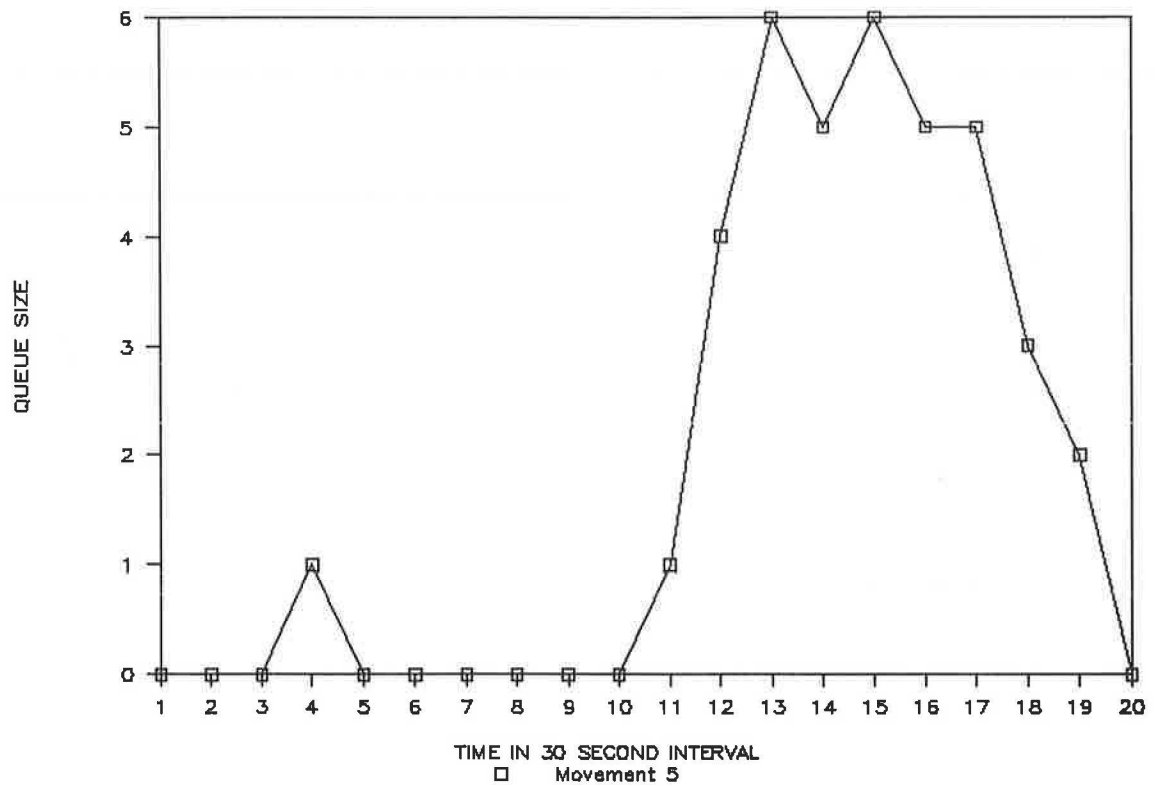


FIGURE 5 Queues for Scenario 2.

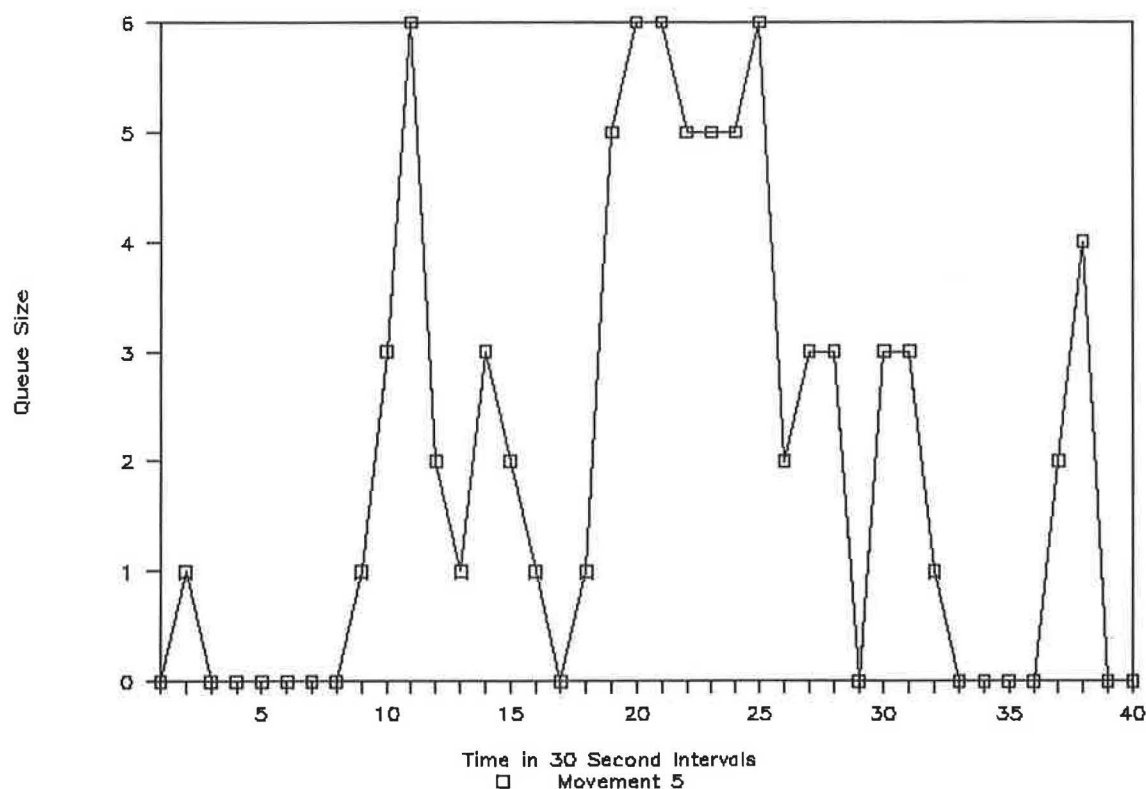


FIGURE 6 Minimum threshold queues for T-intersection.

queues for MVT 5 do attain statistical equilibrium. However, using thresholds higher than the estimated minimum threshold resulted in unstable queues at the intersection. Therefore, it was concluded from the experiment that the estimated minimum threshold was "optimum" for T-intersections.

CONCLUSIONS

Traffic signals have proven very effective in minimizing traffic conflicts at intersections. However, installation of traffic signals at intersections should be well timed to avoid unnecessary traffic delay to the major-street traffic. The MUTCD provides guidelines for determining when traffic signals are required at intersections. Traffic signal installation warrants of the MUTCD involving vehicular volumes are too generalized. These warrants, the aggregated traffic volumes for the major street and the minor street, do not give adequate consideration to the effects of the intersection's geometric configuration.

It has been shown in this paper that the minimum thresholds (volumes) warranting traffic signal installation vary for different intersection configurations. A minimum threshold was estimated for T-intersections. It is expected that this threshold would be useful as a supplement to the existing MUTCD warrants. However, this author strongly recommends that further studies be undertaken to validate this threshold as well as those MUTCD warrants not considered in this study.

REFERENCES

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