A New Approach for Specifying Delay-Based Traffic Signal Warrants

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A methodology is presented that uses both field studies and traffic simulation for developing delay-based traffic signal warrants. The field studies were performed to confirm the validity of the UTCS-1 simulation program. These warrants are based on a competition between two types of intersection control: traffic signals and two-way stop signs. Several of the worst common right-angle intersection configurations were analyzed over the entire spectrum of traffic volumes on their approaches. Analysis of the results led to the definition of criteria, based on volume and delay considerations, for selecting the appropriate type of control. The resulting warrants are expressed in graphical format, and accompanying specifications are given.

The Manual on Uniform Traffic Control Devices (MUTCD) states that a "comprehensive investigation of traffic conditions and physical characteristics of the location is required to determine the necessity for a signal indication..." (6). The assessment of traffic conditions for at-grade intersections is a continuing problem for traffic engineers. Solutions to this problem can take many forms ranging from purely empirical data collection techniques to development of complex theoretical models. Both approaches exhibit strengths and weaknesses. This project took a middle-ground approach in the form of a traffic simulation program validated by comparing the results with those obtained in the field.

The development of a simulation model represents a synthesis of theory and empiricism. To describe the highly variable, stochastic behavior of urban vehicular traffic requires that a microscopic simulation that properly replicates the process be developed. The computer model must be properly calibrated and then validated before it can be applied.

The UTCS-1 simulation model (1, 2) was developed for the Federal Highway Administration primarily to evaluate alternative traffic control policies on urban networks. After it was validated, it was modified (and reduced in size) for the purpose of addressing the single intersection problem. The objective was to use this program to provide the basic data necessary for the specification of delay-based traffic signal warrants. This paper describes the methodology and presents some representative results obtained in the initial phase of this study. Complete documentation appears elsewhere (3).

The basic approach was to specify traffic signal warrants that were firmly based on one or more operational measures of effectiveness (MOEs), which are of primary importance to the traffic engineer. Of necessity, the warrants were expressed in a format that can be applied in an unambiguous manner, avoids complex calculations, and requires a minimum of costly field data acquisition.

Survey results indicated that, although traffic volume data were available at all intersections considered, the direct measurement of MOEs such as vehicle delay and stops was rarely undertaken over an extensive period of the day on all approaches (3). From this information, it was clear that the relationship between the MOE on which the warrants would be based and the data that are directly available to the engineer (geometric descriptors, traffic volumes, etc.) had to be ascertained for the most common right-angle intersection configurations. The medium for providing this relationship was the modified version of UTCS-1.

USE OF SIMULATION TECHNIQUES

There have been an increasing awareness and acceptance of the UTCS-1 simulation model by the traffic engineering profession. In a study using the UTCS-1 as a medium for investigating traffic operations at intersections, Cohen stated (5):

> It can be concluded that the UTCS-1S Single Intersection simulation model has been successfully validated against field data from two intersections differing widely in geometry and location. This indicates that the model has, in addition to its flexibility, a sufficient degree of accuracy to enable it to be of considerable use in the geometric design and signal control of single intersections.

When the UTCS-1 stochastic simulation model is used, controlled experiments can be performed and sensitivity analyses can be conducted to identify the critical factors influencing traffic operations at intersections. Depending on field data alone is not appealing because

1. It is difficult to realize the full range of operating conditions in the field for all intersection configurations;
2. Manual data reduction is certain to introduce errors that may not be detected;
3. Field experimentation costs approximately twice as much as equivalent simulation analysis; and
4. The highly variable nature of traffic flow seriously compromises the validity of results that are aggregated over a time period of, say, 15 min.

This last factor is sometimes overlooked by researchers. It is well-known that the relationship between delay and volume is increasingly nonlinear as the load factor approaches unity. Hence, simple averaging of delay over 15 min yields inaccurate results in this range of volume, when cycle by cycle fluctuations in volume are pronounced.

Figure 1 shows a plot of volume versus time, where the field data are aggregated over four cycle periods (6 min). Even with this aggregation, fluctuations are so pronounced that it is impossible to hold volume constant over a sufficient time period to determine a statistically significant relationship between delay and volume. Applying simulation techniques within the framework of a controlled experiment avoids this problem.

The basic approach adopted was to conduct a competition between fixed-time signal control and two-way stop sign control. Hence, simulation was applied for both types of control at typical isolated, right-angle, four-legged intersections. The simulation results obtained for the two types of controls are presented separately. They are then synthesized in accordance with specified criteria for the development of the proposed traffic signal warrants.

The results of sensitivity studies led directly to the specification of base conditions for the warrants developed under the initial phase of the project. These conditions are

1. Random arrival of vehicles entering the approaches to an intersection,

Figure 1. Variation of traffic volume with time aggregated over 6-min time periods.

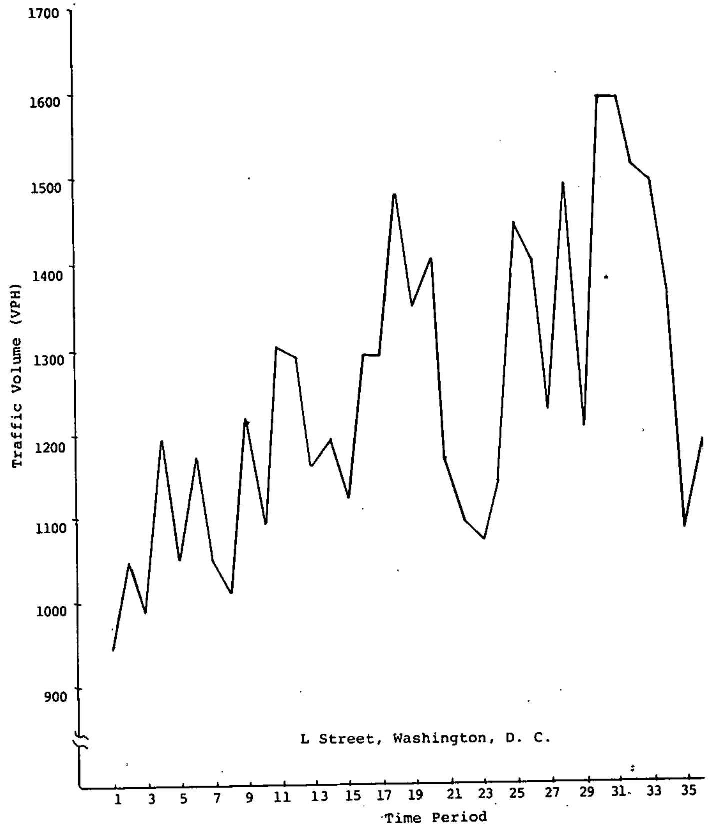


Figure 2. Delay per vehicle for various volume splits.

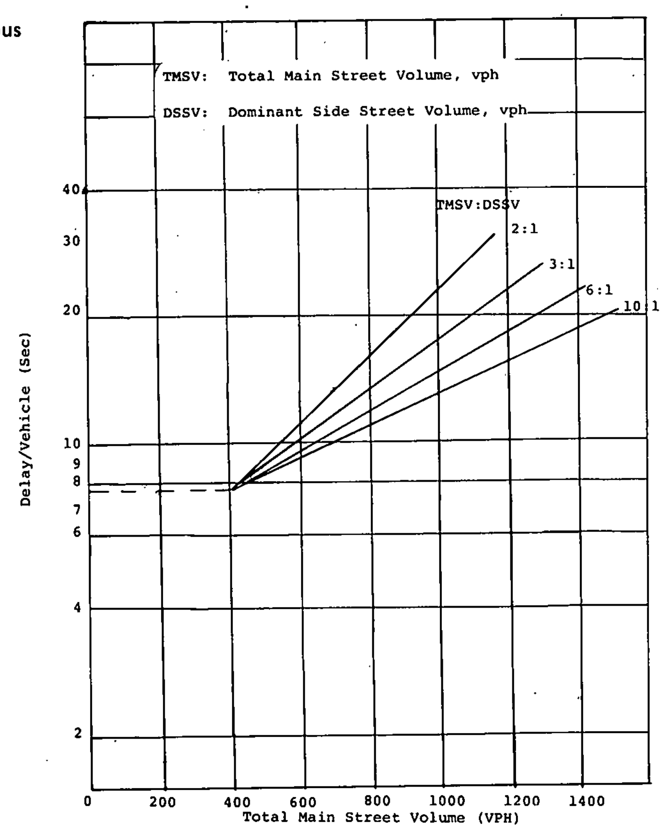


Figure 3. Total delay for various volume splits.

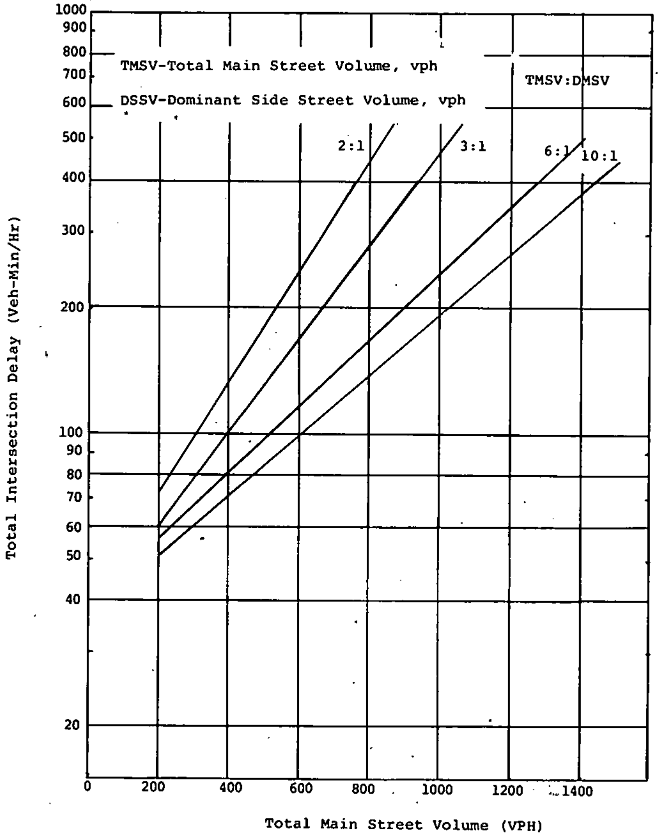
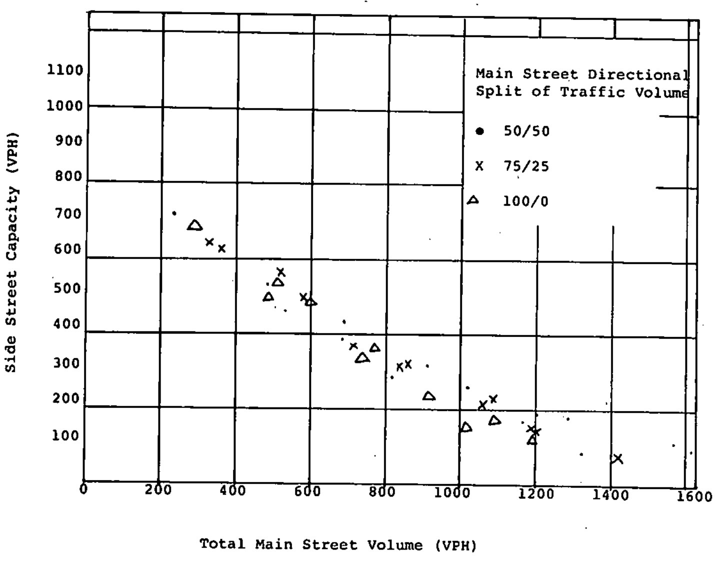


Figure 4. Capacity of a stop-sign-controlled approach.



2. Nominal turning movements and truck traffic,
3. Two values of queue discharge headway (2.1 and 2.4 sec per vehicle), and
4. Three values of mean gap acceptance for side street traffic (5, 6.5, and 8 sec) controlled by a stop sign.

Signalized Intersection Studies

These base conditions were used to perform a large-scale series of signalized intersection simulation runs. Delays specific to an intersection were obtained over the complete range of realizable (undersaturated) main street and cross street volumes.

From the simulation output, plots of per-vehicle and total intersection delay versus total main street volume were drawn for the traffic splits considered (Figs. 2 and 3). The intersection configuration used in these figures is an intersection of two two-way streets where each approach has one moving lane of traffic. For these studies, the values of optimal cycle length and of signal split (7) were implemented.

Two-Way Stop-Sign-Controlled Intersection Studies

Studies were performed to determine the capacity of approaches controlled by two-way stop signs. Once the capacity was determined, the range of volumes covering the region of undersaturated conditions was defined. It was then possible to develop stop sign delay curves through further simulation.

Figure 4 shows a typical capacity plot for side street approaches controlled by stop signs. This figure presents three sets of results, each representing a different directional split of traffic along the main street. As indicated, the effect of the directional allocation of main street traffic on capacity is minimal.

Various values of the mean acceptable gap $\bar{G}$ were also specified. (In Figure 4, $\bar{G}$ = 5.0 sec.) The results indicate that the capacity of an approach controlled by a stop sign is significantly reduced as $\bar{G}$ increases; capacity corresponding to $\bar{G}$ = 8 sec is 30 to 50 percent lower than for $\bar{G}$ = 5 sec over the range of main street volumes.

Based on data obtained from the stop sign capacity studies, the applicable range of side street and main street volumes for each configuration and mean acceptable gap was defined. Simulation studies were conducted to relate the delay measures (for side street vehicles only) to main street volume for each of three values of mean acceptable gap. Figures 5 and 6 show representative results for $\bar{G}$ = 6.5 sec.

ANALYSIS OF SIMULATION RESULTS

After the delay curves for both signalized and stop-sign-controlled intersections were developed, they were combined to form composite plots. Figure 7 shows a representative composite plot of delay per vehicle; Figure 8 shows a similar plot for total intersection delay. On all plots the same pattern is evident: When main street volumes are low, stop-sign-controlled intersections exhibit significantly less delay than do signalized intersections. As total main street volume increases, delay per side street vehicle (facing the stop sign) quickly exceeds the per-vehicle delay experienced by vehicles at signalized intersections. Total delay at intersections controlled by two-way stop signs, however, generally remains less than that at signalized intersections until main street volumes are quite high.

This relative disparity in behavior between mean delay per vehicle and total intersection delay is a key factor in the development of traffic signal warrants. It is clear that a trade-off is necessary to balance the dual objectives of minimizing total intersection delay and eliminating excessive per-vehicle delay.

Data shown in Figure 9 illustrate the approach taken. Figure 9(a) shows the variation in total delay experienced by vehicles on all approaches to an intersection controlled by a fixed-time, two-phase signal and by a two-way stop sign. Figure 9(b) shows the mean delay per vehicle for these two control types. These plots are con-

Figure 5. Delay per vehicle for various volume splits; side street controlled by stop sign.

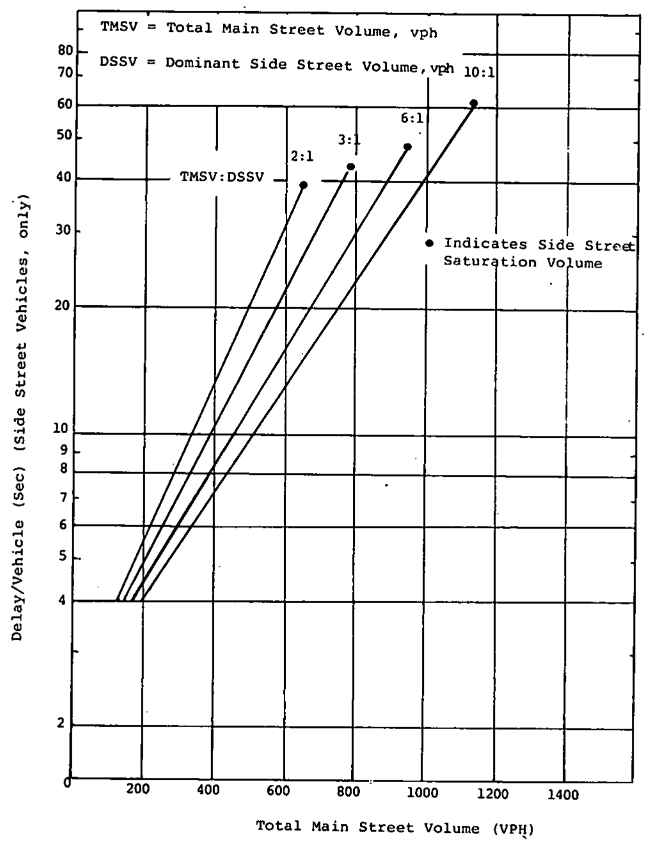


Figure 6. Total intersection delay for various volume splits; two-way stop sign control.

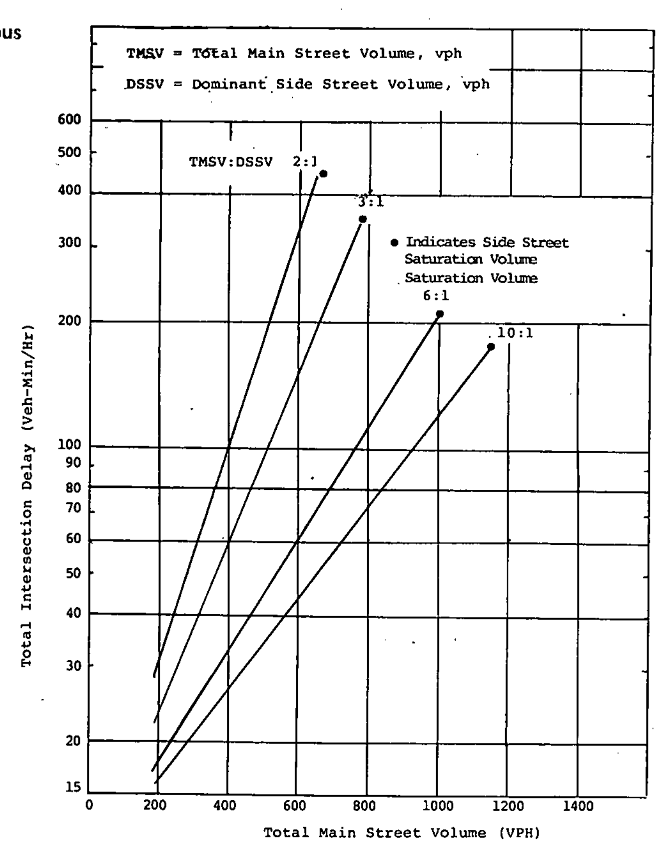


Figure 7. Composite delay per vehicle curves ($\overline{G}$ = 6.5 sec).

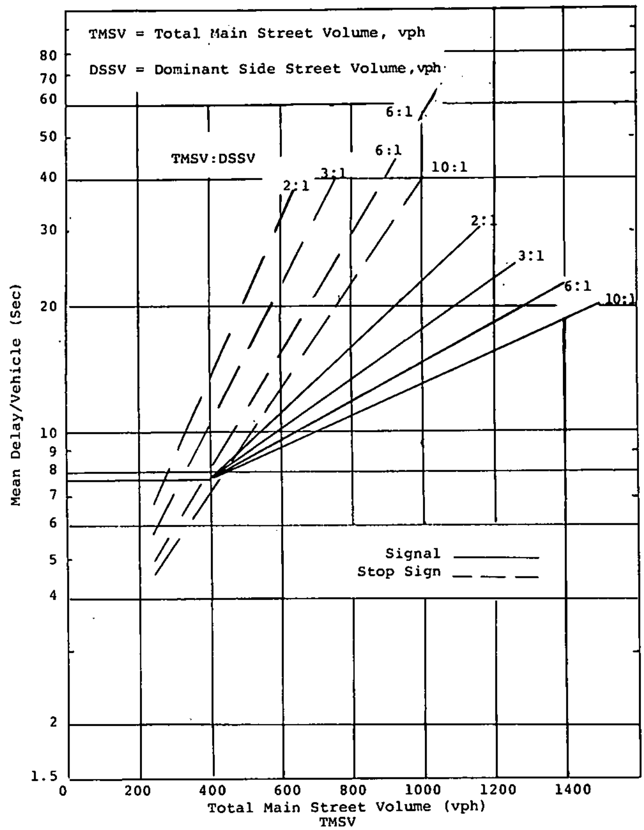


Figure 8. Composite total intersection delay curves ($\overline{G}$ = 6.5 sec).

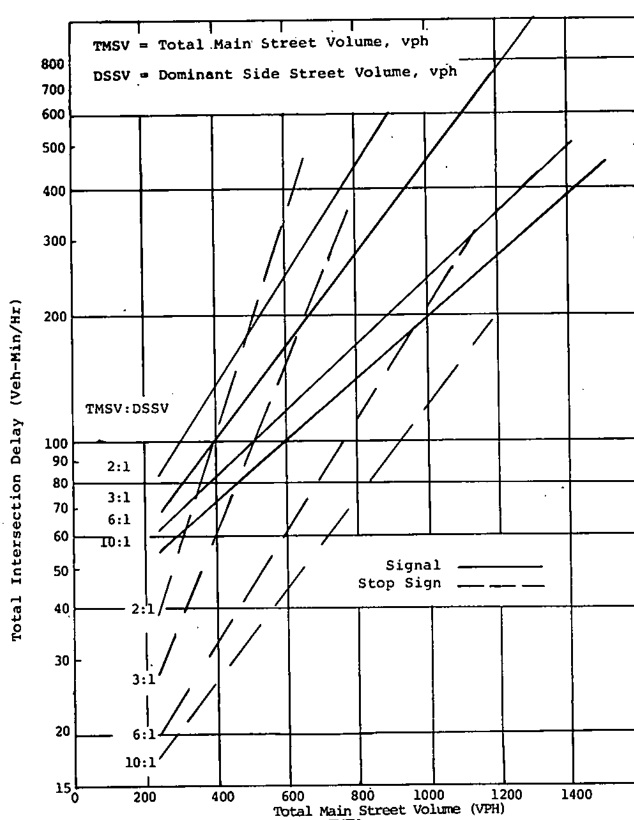


Figure 9. Conceptual representation of delay-volume relationships at isolated intersections.

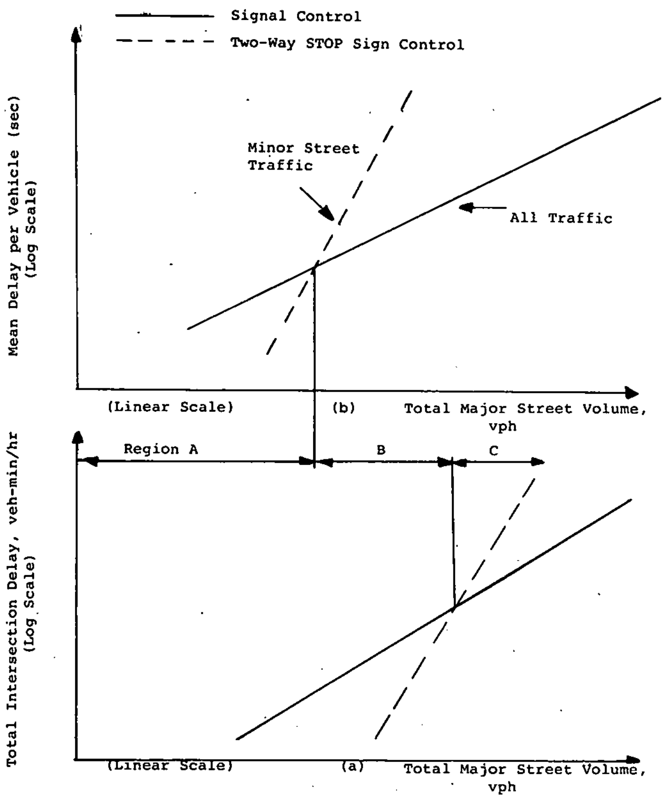
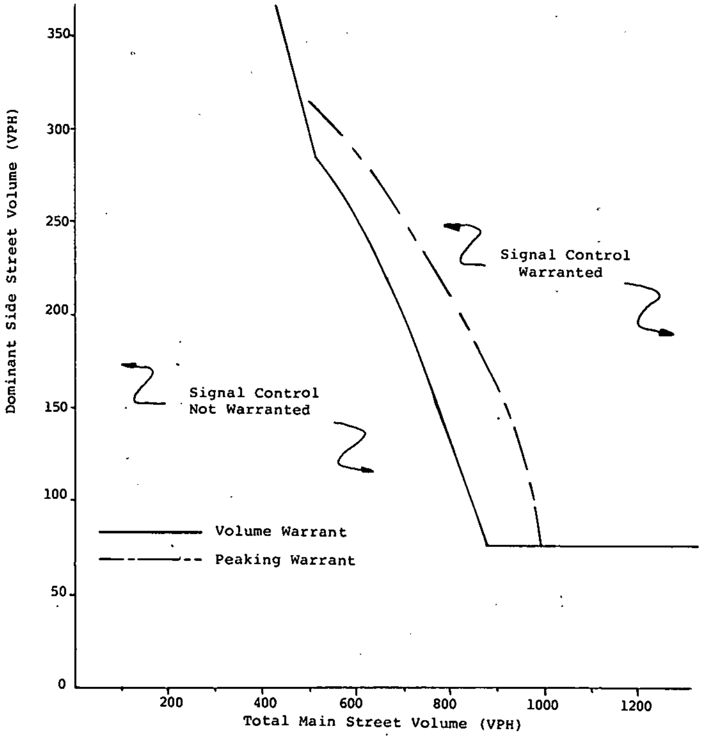


Figure 10. Typical volume and peaking warrants.



ceptual generalizations of those in Figures 7 and 8. Note that the value of main street volume that produces equal values of mean delay per vehicle for the two types of control is considerably lower than the value of main street volume that produces equal total intersection delay. This must always be the case when the total major street volume exceeds the total minor street volume. Three volume regions are identified in the figure.

Region A

In this region, the installation of a signal will degrade performance of all traffic. Both total intersection delay and mean delay per vehicle will be greater than that with two-way stop sign control. Clearly, the proper choice of control device in this region is the two-way stop sign.

Region B

In this region, installation of a signal will benefit the vehicles on the minor street approach but will produce disbenefits to the (larger number of) vehicles on the major street. It is in this region that the conflict between the two cited objectives prevails. Installation of a signal will act to equilibrate per-vehicle delay among those vehicles on the competitive approaches, thus satisfying the second objective, but will increase total intersection delay in the process, thus contradicting the first objective. Resolving this difficulty through an acceptable trade-off between the two objectives yields the basis for the proposed traffic signal volume warrants.

Region C

In region C, the installation of a signal satisfies both objectives; the proper choice of control device is clearly that of a traffic signal.

It is clear that the traffic signal warrants will be expressed in terms of those traffic conditions that lie within region B. (The current MUTCD volume warrants fall within this region.) It is necessary, then, to quantify the aforementioned trade-off, based on a concept of equity of service. Although it is necessary to assign priority to streets, it is unfair, impolitic, and conducive to unsafe driver behavior to impose excessive delay to a minor component of traffic in order to provide unimpeded service to a major component. A mean value must be determined that corresponds to tolerable delay for side street vehicles controlled by a stop sign. A survey of practicing traffic engineers across the country (3) yielded the mean value of 28 sec per vehicle.

Also, a number of traffic volume thresholds must be specified, including

1. A lower threshold for hourly side street traffic volume below which a traffic signal installation should not generally be considered and
2. A lower threshold for hourly total intersection volume below which a signal installation should not generally be considered.

It is generally not cost-effective to install a traffic signal when the peak-hour side street traffic volume is below some limiting value. Hence, the following thresholds have been adopted:

Lanes	vph
One	75
Two	100

Although these values are somewhat arbitrary, they represent a consensus of opinion and current practice.

PRESENTATION OF WARRANTS

Five criteria for the specification of delay-based traffic signal warrants have evolved from this study (3):

1. Minimum total intersection volume,
2. Minimum side street volume,
3. Equity of total intersection delay,
4. Tolerable side street delay, and
5. Equity of service.

Applying these criteria appropriately to the simulation delay data permits delay-based volume and peaking traffic signal warrants to be defined over the entire volume range of interest for intersection configurations that are most often candidates for signalization. The volume warrant specifies that a signal should be installed at an intersection if it is satisfied for each of any 4 hours. The peaking warrant is designed to assess short-term demands to determine whether a traffic signal is necessary; the need for a signal is indicated when this warrant is satisfied for any 2 hours.

Figure 10 shows the format for the volume and peaking warrants; a separate graph is provided for each intersection configuration considered. To apply the warrant, the engineer determines the total main street traffic volume and the associated dominant (higher) side street traffic volume for each hour. Hence, 1 hour of these data represents one point on the warrant figure. If any four of these points lie to the right of the solid line in the indicated region, then a traffic signal is warranted. Similarly, if two of these points lie to the right of the broken line, then a traffic signal is warranted, even if the first condition is not satisfied. If neither condition is satisfied, a traffic signal is not warranted on the basis of delay considerations.

The primary departures of these traffic signal warrants from those specified in sections 4C-3, 4 of the MUTCD (6) are

1. They synthesize MUTCD traffic signal warrants 1, 2, and 8,
2. They are defined over the entire range of admissible volumes in place of discrete tabulations,
3. A peaking warrant is presented, and
4. Warrants are based on the four highest volume or two highest peaking hours rather than on the eight highest volume hours.

Furthermore, it is believed that these traffic signal warrants exhibit the following advantages over those currently specified in the MUTCD:

1. They are based on that MOE most readily perceived by the motorist, i.e., delay;
2. The warrant curves are internally consistent in accordance with well-defined criteria;
3. The graphical presentation provides the engineer with a visual impression of the intersection status with respect to its need for a traffic signal (e.g., if data do not satisfy the warrant but there is a cluster of points near the curve, then this evidence could indicate a near-term requirement for upgrading the control there);
4. This graphical presentation could be an effective technique for responding to citizen groups that petition for a traffic signal where it is not warranted; and
5. The shorter time scale (4 versus 8 hours of data) reduces the engineer's data gathering requirements and associated cost and is more responsive to the characteristic peaking of traffic demand.

Ongoing research will extend the warrants to those intersections that experience heavy turning movements and will extend the number of configurations as well. In addition, a systems warrant will be developed for signals that are closely spaced.

ACKNOWLEDGMENT

This work was sponsored by the American Association of State Highway and Transportation Officials in cooperation with the Federal Highway Administration and was conducted under the National Cooperative Highway Research Program.

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