Proposed Procedure for Selecting Traffic Signal Control at School Crossings

JAMES A. BONNESON AND JOSEPH D. BLASCHKE

This paper describes the current criteria used to determine the need for traffic control at school crossings. It discusses the background and assumptions used in establishing these current criteria and points out a few of its deficiencies. Based on this assessment, a methodology is proposed that is intended to improve on the current criteria. This methodology has the advantages of enabling more equitable treatment of vehicular and pedestrian traffic as well as allowing for easier application. The current procedure for determining the need for traffic signal control is based on a field study technique that yields the length of time needed by pedestrians to cross the street and the frequency with which gaps of this duration occur in the vehicular traffic stream. The proposed procedure is similar to the current procedure; however, by assuming that the distributions of pedestrian and vehicular arrivals are random, time-dependent processes, the Poisson distribution can be used to estimate the gap duration and its frequency of occurrence. The intent of this approach is to eliminate the need to conduct a field study at locations where the assumption of random arrivals is valid. As a result of this investigation, a procedure is proposed that incorporates the intent of the current procedure but is much simpler to apply. Additional criteria have been added that address the issue of interruption of pedestrian flows and the need for a minimum pedestrian volume. The goal of this procedure is to provide a means of ensuring the uniform application of traffic control devices and to avoid the unnecessary installation of traffic signals.

The safety of children traveling between home and school is a highly sensitive subject. There are often conflicting opinions among citizens and public officials about what must be done to ensure the safety of the children. Citizens typically want additional police officers, crossing guards, and traffic controls on any street they feel is "potentially dangerous." Public officials representing the school and the city must respond to the citizen's concerns by determining a proper course of action. Their determination is founded on the desire to maximize both motorist and pedestrian safety, but it must be tempered by the effective use of limited funding resources and the application of reasonable and uniform traffic control policies. (The term "pedestrian" is used throughout to refer to school children walking along, adjacent to, or across the roadway.)

Engineering studies have shown that the uniform application of reasonable traffic control procedures will improve public understanding and acceptance of any control measure. In contrast, use of non-uniform procedures or controls creates confusion and lessens the respect given to them by pedestrians and motorists alike. Hence, establishing and adhering to a set of reasonable and uniform criteria for applying traffic control is a desired goal because it ensures equal treatment at similar locations and moderates the influences of emotion and bias.

This paper describes the current criteria used to determine the need for traffic control at school crossings. It discusses the background and assumptions used in establishing the current criteria and points out a few of its drawbacks. Based on this assessment, a new methodology is proposed that is intended to improve on the current criteria. This methodology has the advantages of enabling more equitable treatment of vehicular and pedestrian traffic as well as allowing for more convenient application.

STATEMENT OF PROBLEM

According to the Uniform Vehicle Code, motorists must yield the right-of-way to pedestrians within crosswalks or within unmarked crosswalks at intersections (*1*). From this it might be concluded that signal control is never needed because motorists should stop whenever a pedestrian crosses within a crosswalk. However, the reality of the situation is that motorists do not always yield to pedestrians for a variety of reasons. Hence, there is a need for signal warrants at pedestrian crossings, particularly when the pedestrians are school-age children.

A procedure for establishing school crossings is currently addressed in the *Manual on Uniform Traffic Control Devices* (MUTCD), Traffic Signal Warrant 4—School Crossing (*2*). In particular, the manual suggests that a signal may be warranted when "the number of adequate gaps in the traffic stream, during the period when the children are using the crossing, is less than the number of minutes in the same period (*2*,p.4C-5)." The intent of this warrant is to limit the time a child must wait to cross to less than 60 sec. This maximum has been established because studies have shown that pedestrians will become impatient after waiting 30 sec to cross and will edge out into the roadway after 40 sec (*3–6*).

The application of this warrant requires the conduct of a traffic engineering study to determine the duration of an "adequate" gap and the availability of these gaps in the vehicular traffic stream. Although this type of study is simple to conduct, it has the drawback of consuming both time and resources. Another drawback of this warrant is that it considers only the delay to pedestrians, which is not necessarily the safest or best operation of the crossing. For example, at those crossings where pedestrian flows are characterized by high volume and random arrivals, it is entirely likely that motorists (stopped

Texas Transportation Institute, Texas A&M University System, College Station, Tex. 77843.

for pedestrians) will experience near 100 percent stopping and high delays and will often be seen exhibiting the same impatient attitudes that are displayed by pedestrians waiting for gaps in vehicular traffic. This situation often precipitates unsafe actions, such as motorists "weaving" through the pedestrian streams, diverting onto nearby streets, and disregarding the basic rules of vehicular and pedestrian right-of-way at intersections.

Other drawbacks of the MUTCD school crossing warrant and its application include the following:

- It does not have a minimum pedestrian flow rate below which signal control should not be considered. As a result, it could take only one school-age pedestrian wanting to cross a major arterial to "warrant" a signalized crossing.
- The procedure for determining adequate gap size does not reflect the distribution of the arriving pedestrian flow but, rather, the size of the pedestrian group accepting a gap provided by the vehicular stream. Hence, the gap size study is affected by the distribution of vehicular gaps and, as a result, is biased toward higher group sizes.
- The procedure does not identify a minimum period or duration during which the pedestrian flow rate would equal or exceed the minimum rate.

Each of these drawbacks has been considered for this paper and will be discussed in the following sections.

Determining the Need for School Crossing Control

The procedure for determining the duration of an "adequate" gap and the frequency of its occurrence was originally described in an Institute of Transportation Engineers (ITE) publication (*3*). The procedure has since been reproduced in the *Transportation and Traffic Engineering Handbook* (*7*). This procedure is based on field survey techniques in which the size of the pedestrian groups crossing the roadway and the duration of the gaps between vehicles traveling on the roadway are recorded for a common interval of time. Obviously, this interval is associated with the periods before and after school when children are crossing the roadway.

The adequate gap time is calculated by using the following formula:

$$G = R + (W/S) + K * (N - 1) \quad (1)$$

where

G = adequate gap time (sec),
R = pedestrian perception and reaction time (sec) (assumed to be 3.0 sec),
W = curb-to-curb width of the street crossed (ft)
S = walking speed of child (ft/sec) (assumed to be 3.5 ft/sec),
K = time between successive rows (sec/row) (assumed to be 2.0 sec/row),
N = number of rows in the 85th percentile pedestrian group size rounded up to the next integer value $\{= \text{integer}[(Q85/n) + 1]\}$,
$Q85$ = 85th percentile pedestrian group size observed during the field survey, (pedestrians/group), and
n = number of pedestrians in each "row" crossing the street (assumed to be five pedestrians per row).

This study would be conducted during a normal school day during the heaviest period of pedestrian crossing activity.

Once the duration of the adequate time gap is known, the number of gaps of equal or greater size in the vehicular traffic stream is determined and compared with the number of minutes that transpired during the period of pedestrian activity. If the number of adequate gaps is fewer than the number of minutes (implying an average wait of more than 60 sec), then a signal may be installed to artificially create the necessary gaps.

Basis for Proposed Procedure

Recognizing the limitations of the current procedure, a proposed procedure was formulated that could be used to determine the pedestrian and vehicular volume conditions that would require some type of control to improve safety and minimize delay. The proposed procedure for determining the need for school crossing control is based on and intended to supplement the existing warrant criteria. It is offered as a tool to simplify the evaluation of MUTCD's signal warrant criteria for school crossings; it also addresses some of the drawbacks of the ITE field study procedure. The proposed procedure is based on the following assumptions:

- Both pedestrian and vehicular flows are random processes.
- The assumed values used in Equation 1 are reasonable.
- The average wait of 60 sec describes the threshold of pedestrian patience.

If these assumptions do not hold or if the situation requires special consideration for other reasons, then the ITE field study procedure should be used. The development of the proposed new procedure is described in the next section.

DEVELOPMENT OF THE PROPOSED PROCEDURE

The proposed procedure is directed toward the development of a series of graphs that relate traffic volume, pedestrian volume, and the type of control needed. The graphs are similar to those used for MUTCD Signal Warrant 11—Peak Hour Volume—in that the volume levels are assigned to the horizontal and vertical axes and the recommended control is identified by a region within the graph. The intent of this procedure is to avoid the need for a field study to determine the adequate gap size or the frequency of its occurrence. The steps in the procedure's development are described in the following sections.

Determination of Adequate Gap

The procedure for determining the adequate gap (Equation 1) was used without modification, recognizing that some of the assumed values may not be universally accepted. In particular, it has been suggested by some that the reaction time be less than 3.0 sec (*6,8*). In addition, it has been suggested that the width of the street be reduced by the width of the far-side curb parking lane (*9*). It has also been implied that all pedestrians will cross as a single row (i.e., $N = 1$) regardless of

the pedestrian volume (*6,8–10*). These deviations are recognized here only for completeness; the values recommended elsewhere (*7*) are used for this analysis.

By using the assumed values stated in Equation 1, the size of adequate gap was calculated by using the following equation:

$$G = 3.0 + (W/3.5) + 2.0 * (N - 1) \quad (2)$$

where

G = adequate gap time (sec)
N = integer[$(Q85'/5) + 1$],
$Q85'$ = estimated 85th percentile pedestrian group size, $(q*t) + k * (q*t)^{0.5}$
q = pedestrian flow rate averaged over 15 or more minutes (pedestrians/second)
t = time interval between acceptable gaps (sec) (equal to 60 sec or 1 gap/min),
k = number of standard deviations the 85th percentile volume is away from the mean volume (assumed to be 1.0), and
$(q*t)^{0.5}$ = standard deviation of the Poisson distribution.

Using the above assumed values, the number of rows of pedestrians (N) that wish to cross each minute can be calculated as

$$N = \text{integer}\left[\frac{(q*60) + (q*60)^{0.5}}{5} + 1\right] \quad (3)$$

By using Equations 2 and 3, the size of the 85th percentile pedestrian group size can be estimated given only the pedestrian flow rate and the width of the street to be crossed. Values of the adequate gap size (G) have been calculated for various roadway widths and are shown in Figure 1.

This approach attempts to model group size as a function of arriving demand and not as it would be observed in a field study in which the distribution of gaps in the vehicular stream would artificially "bunch" the pedestrian groups. What is typically measured by a study of pedestrian flow at the crosswalk is not the true demand versus the time profile but the maximum flow rate through a bottleneck. Based on this observation, it is suggested that the traditional study of demand at the crosswalk will likely yield an inflated estimate of the group sizes of arriving pedestrians. The consequences of overestimating pedestrian group size would be the exclusion of traffic gaps that are, in fact, sufficient for pedestrian use.

Frequency of Adequate Gaps

The calculation of the frequency of adequate gaps is based on the assumption of random arrivals. This assumption implies that the probability that any one gap is equal to or greater than the adequate gap (G) is

$$P(g > G) = \exp(-v * G) \quad (4)$$

where

G = adequate gap time from Equation 1 or 2 (sec),
v = vehicular flow rate averaged over 15 or more minutes (vehicles/second), and
$\exp(x)$ = the base of the natural log e (2.718...) raised to the power x.

From this relation, the number of adequate gaps can be calculated by using

$$PG = [v*t * \exp(-v * G)] / [1 - \exp(-v * G)] \quad (5)$$

where

PG = number of adequate pedestrian gaps [gaps/interval (t)] (defined as one gap/interval),
v = vehicular flow rate averaged over 15 or more minutes (vehicles/second),
t = time interval between acceptable gaps (sec) (equal to 60 sec), and
G = adequate gap time from Equation 1 or 2 (sec).

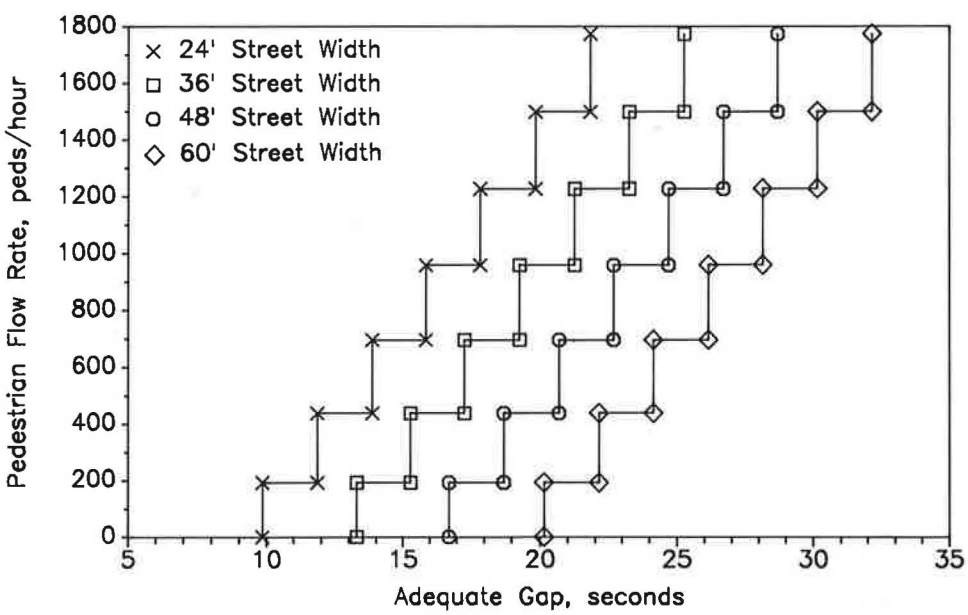

FIGURE 1 Adequate gap versus pedestrian flow rate.

From Equation 5, the maximum vehicular flow rate can be calculated that will yield one gap of adequate size at an average of every 60 seconds. The relation used in Equation 5 is an extension of other gap relations that have been used by other authors but does not share their limitations. These other relations include

$$PG = v * t * \exp(-v * G) \quad (6)$$

$$PG = (60/G) * \exp(-v * G) \quad (7)$$

Equations 5, 6, and 7 are compared in Figure 2. As shown in this figure, Equation 6 is in close agreement with Equation 5 under high-volume conditions, but it also implies that there is a maximum size to the gaps in the traffic stream. The problem with Equation 6 is its failure to recognize the potential for more than one pedestrian group to cross during the longer traffic gaps. Additional insight into this problem is described elsewhere (*10*).

Equation 7 also appears to be in close agreement with Equation 5 under low-volume conditions. The discrepancy between these equations appears in the higher volume range. Equation 7 yields much too conservative an estimate of the maximum vehicular flow rate for small gap sizes. The problem with Equation 7 is that it estimates the number of gaps that can occur in one minute (i.e., $60/G$) rather that the actual number of gaps in traffic per minute (i.e., $v*t$). As a result, it underestimates the number of gaps available for pedestrian use, particularly for higher volume conditions.

Based on the preceding discussion, Equation 5 appears to agree with Equations 6 and 7 under specific volume conditions. The advantage of Equation 5 is that it yields reasonable estimates over the entire range of volume conditions. In recognition of these benefits, Equation 5 is used in the development of the proposed procedure.

By applying Figures 1 and 2, it is possible to determine the size of the adequate gap required by pedestrians and whether or not gaps of this size are available in the existing vehicular stream. If the combination of existing vehicular traffic and pedestrian gap length is so great as to fall above the solid line in Figure 2, then signal control is warranted.

Interruption of Pedestrian Flow

Occasionally the volume of pedestrians is so high that, once given the right-of-way, they do not relinquish it for a considerable time. This can result in lengthy delays for motorists and is the reverse of the problem just described (i.e., pedestrians delayed by motorists). Motorists can, and should be expected to, tolerate longer delays than pedestrians because of the added protection of motorists from inclement weather and because of the added danger to pedestrians standing along the roadside. However, a threshold level of pedestrian volume should be determined wherein some artificial means of interruption (such as a traffic signal or crossing guard) is necessary to allow a minimum number of vehicles to pass. The following discussion describes the calculation of such a threshold.

Based on the assumptions of random arrivals of pedestrians and that motorists will continue to yield as long as pedestrians are in the crosswalk, Equation 5 is again used to calculate the number of available gaps. However, this time the available gaps are in the pedestrian flow and they are entered by a standing queue of vehicles. The equation used is defined as follows:

$$VG = NL * [q*T* \exp(-q * a)]/[1 - \exp(-q * b)] \quad (8)$$

where

VG = maximum number of adequate vehicular gaps (gaps/hour),
q = pedestrian flow rate averaged over 15 or more minutes (pedestrians/second),
T = duration of pedestrian crossing activity (sec) (assumed to be 3600 seconds),

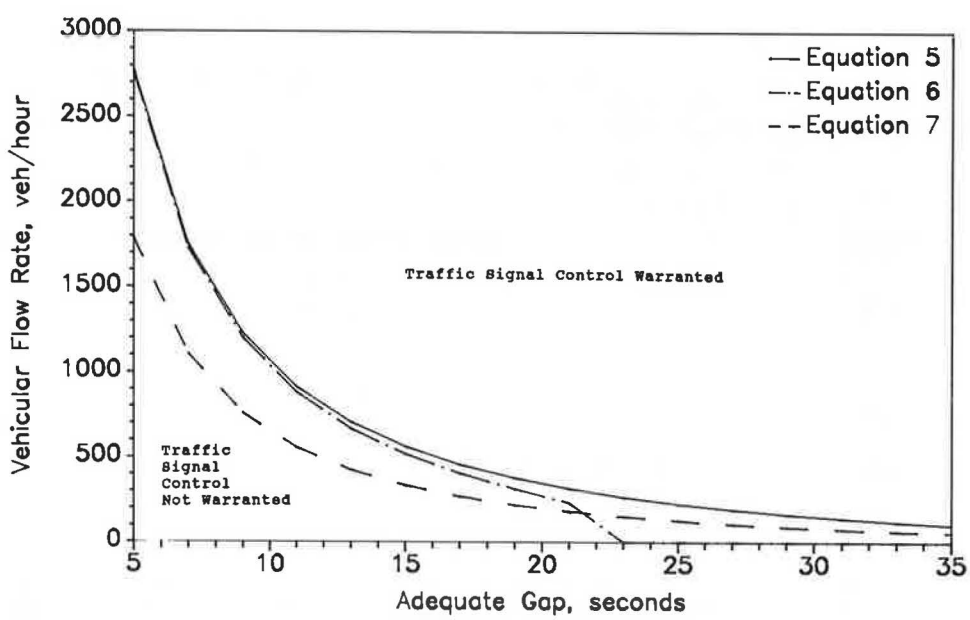

FIGURE 2 Adequate gap versus vehicular flow rate.

a = minimum gap for one vehicle to cross (sec) $r + (W/S)$,
r = motorist perception and reaction time (sec) (assumed to be 2.0 seconds),
W = curb-to-curb width of the street crossed (ft),
S = walking speed of child (ft/sec) (assumed to be 3.5 feet/second),
b = minimum headway between vehicles on a two-way, two-lane street (assumed to be 2.57 sec), and
NL = number of traffic lanes within street (assumed to be 2 for $W < 40$ ft and 4 for $40 < W < 65$ ft).

Recognizing that this represents the maximum number of vehicles that can cross through a pedestrian flow (i.e., vehicular capacity), a lower value was selected that reflected a more stable, nominal delay condition. Consulting the *Highway Capacity Manual*'s level-of-service descriptions for unsignalized intersections, it was found that a reserve capacity of 100 to 199 vehicles per hour per lane (vphpl) described a condition of "long traffic delays" (*11*). This was denoted as level-of-service "D." Based on this description, it was determined that the vehicular capacity calculated from Equation 8 should be reduced by 100 vphpl. Thus, the threshold values of pedestrian volume that would still yield a level-of-service "D" condition for traffic were calculated as

$$NG = VG - NL * 100 \tag{9}$$

The number of gaps available (NG) was further adjusted to account for an assumed 55/45 percent directional split in vehicular demand.

Minimum Pedestrian Flow Rate

The reason for establishing minimum pedestrian and vehicular flow rates is to avoid the indiscriminate installation of traffic signals. Installing and maintaining unwarranted signals will lead to intentional violation, increased hazard, and unnecessary delay. Furthermore, the cost of installing and maintaining unwarranted signals does not constitute an efficient use of limited safety funds.

Recognizing that minimum volume warrants are more often based on rational judgment and experience rather than on theoretical analysis, a review of the literature was conducted to determine if any formally adopted pedestrian volume warrants existed. One agency that has established such warrants is the California Department of Transportation (CDOT) (*12*). These warrants are reasonable and consistent with the intent of this paper. More importantly, they imply that there are minimum pedestrian and vehicular volumes below which signal control is not necessary. In recognition of this general agreement, the minimum pedestrian flow rates developed for the proposed procedure are loosely based on CDOT warrants for school crossing traffic signals.

In general, it is recommended that the minimum pedestrian flow rate be established at 100 per hour. This minimum may be reduced to 50 pedestrians per hour if

1. A crossing is being considered at a location where the nearest existing traffic signal, controlled crossing, or pedestrian overpass is over 300 ft away, or
2. The crossing is in an area where adequate and safe sidewalks are not available to and from the location with the existing signal, crossing, or overpass.

In addition, it is suggested that a minimum of 500 pedestrians use the crossing during an average day. If the crossing is in a rural area or when the 85th percentile speed exceeds 40 mph, then 70 percent of the above minimums should be used.

The period of analysis should correspond to the period of peak pedestrian demand. However, the minimum period of analysis is a 15-minute interval (even if the duration of pedestrian demand is shorter). The vehicular and pedestrian flow conditions must occur during the same peak period and must be representative of the average day.

The intent of these minimums is to eliminate the unnecessary installation of signalized pedestrian crossings. This is not to suggest that pedestrian flow rates less than these minimums do not need traffic signal control but only that other forms of control or transport (of the students across the street) should be considered.

Combination of Pedestrian and Vehicular Demand

As discussed at the beginning of this section, the goal was to develop a graph with the pedestrian and vehicular flow rates on horizontal and vertical axes, respectively. The approach just described accomplishes this goal. Furthermore, this approach incorporates the determination of adequate gap size for pedestrian flow rates and, thereby, eliminates the need to conduct the ITE field study procedure. This procedure also considers the possible need for interruption of pedestrian flows to maintain reasonable vehicular operation.

All variables were eliminated in the derivation of this procedure except the width of the cross street (W). As a result, a series of graphs were constructed for selected street widths. These graphs are shown in Figures 3, 4, 5, and 6 for street widths of 24, 36, 48, and 60 ft, respectively. There are essentially three determinations (identified by regions) that can be made from these graphs based on the known vehicular and pedestrian flow rates:

1. Pedestrian and vehicular demands are sufficiently light that no control is necessary.
2. Pedestrian demand is heavy and vehicular demand is light (or vice versa) and therefore some type of control is necessary to interrupt pedestrians to maintain a minimal level of vehicular service. The control considered may include a crossing guard or a traffic signal.
3. Both pedestrian and vehicular demands are sufficiently heavy that a traffic signal may be needed to separate the two conflicting flows.

Each of these regions is identified on the graphs where appropriate. The left-most vertical boundary represents a minimum flow rate of 100 pedestrians per hour. This boundary should be shifted left if a lower minimum flow rate is selected.

Validation of Proposed Procedure

Because of a limited amount of field data, pedestrian crossing activity was computer simulated for the purpose of validating

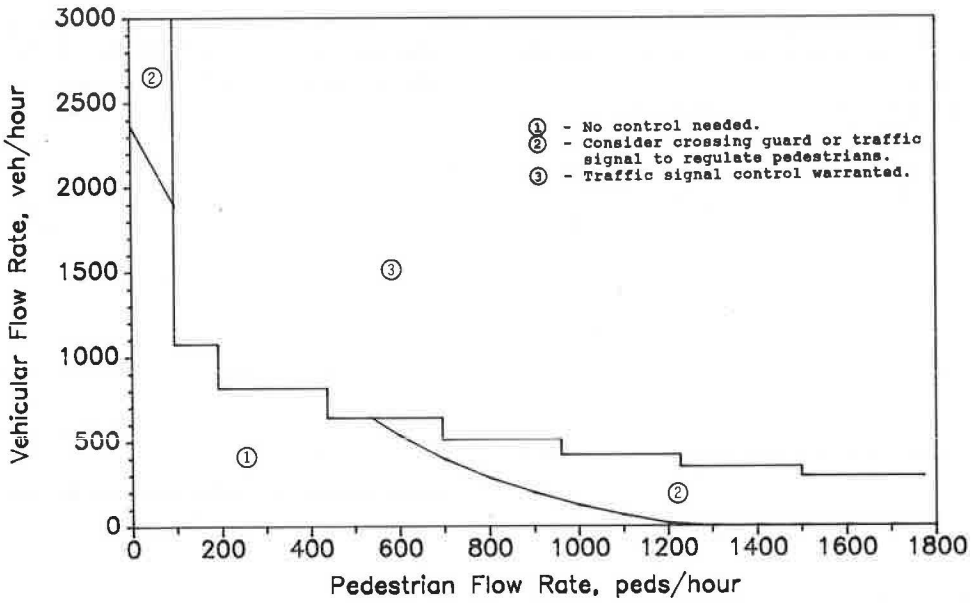

FIGURE 3 Pedestrian versus vehicular flow rate: 24-ft street width.

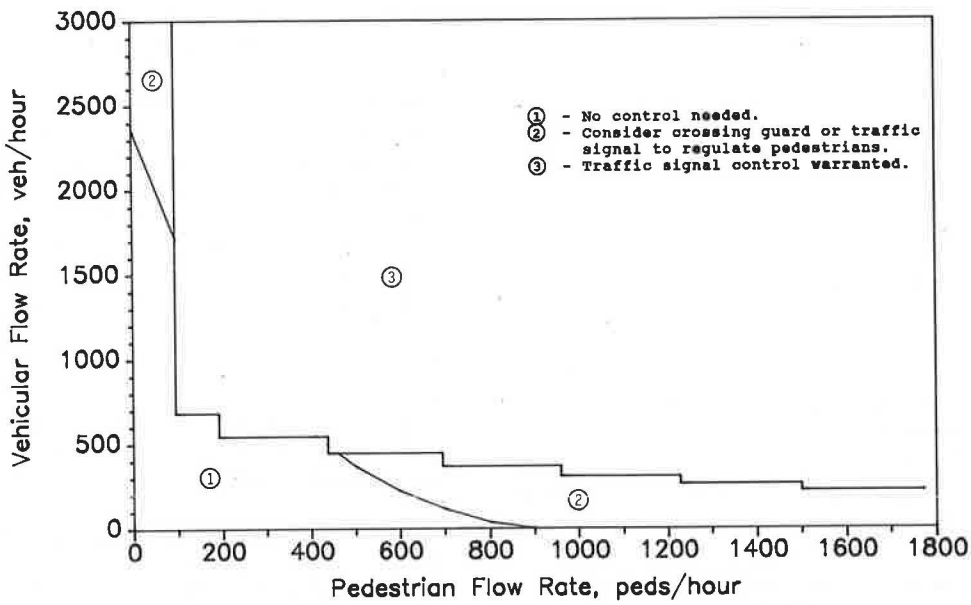

FIGURE 4 Pedestrian versus vehicular flow rate: 36-ft street width.

the proposed procedure. In particular, that portion of the procedure that theoretically determines the adequate gap size and the frequency of these gaps was compared with simulation results for similar demand conditions.

Before the results are discussed, it will be helpful to recall the objective of the ITE field study procedure (and the procedure proposed in this paper). This objective is to limit the time pedestrians must wait for an adequate gap. In an attempt to satisfy this objective, ITE proposed two field studies that are intended to ensure that 85 percent of all pedestrians can find an adequate gap in less than 1 minute, on average. Thus, in an indirect manner, the ITE procedure attempts to limit the delay experienced by 85 percent of the pedestrians to less than 60 seconds. It is this delay criterion that was used in the simulation results for comparative purposes.

The results of the simulation are shown in Figure 7. As alluded to in the previous paragraph, the simulation data reflect the threshold combination of demands that would cause 85 percent of all pedestrians to experience delays of 60 seconds or less. In general, the ITE and proposed procedures appear to yield results that are consistent with the delay criterion, which is not surprising since they were both formulated to do just that. In summary, these simulation results indicate that the proposed procedure can predict demand combinations that yield pedestrian delays of about 60 seconds or less; which is consistent with the procedure's original objective.

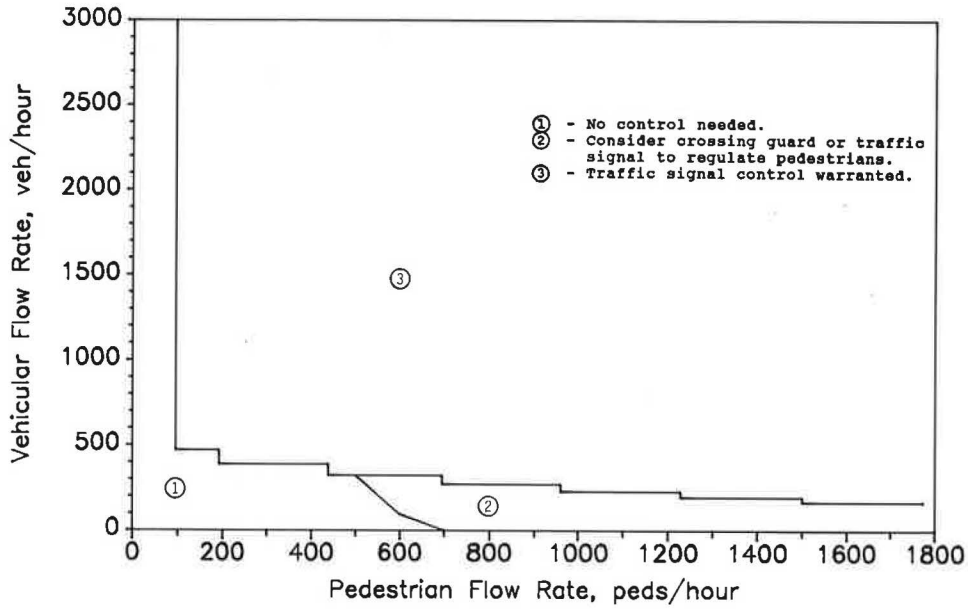

FIGURE 5 Pedestrian versus vehicular flow rate: 48-ft street width.

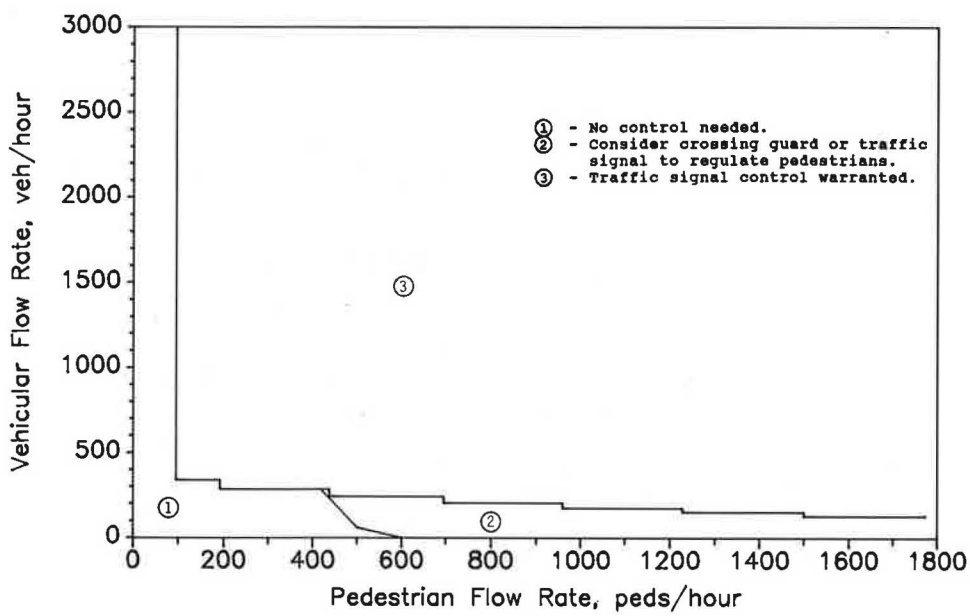

FIGURE 6 Pedestrian versus vehicular flow rate: 60-ft street width.

PROPOSED PROCEDURE

The following procedure is suggested for determining the need for traffic control at school crossings. It is intended as a substitute for the ITE field study procedure (*3*) and should be used only when the assumptions stated in the Statement of Problem section are valid. In any case, engineering judgment must be used to ultimately determine the need and type of traffic control to use at any school crossing.

The first step is to determine the period and duration of highest pedestrian activity (the minimum duration is 15 minutes) at the crossing of interest. This duration should be no longer than the period of pedestrian demand. Typical durations range from 30 minutes to 2 hours.

The second step is to determine the total daily pedestrian demand for the same crossing. If the minimum pedestrian flow rate and volume levels can be satisfied, then the analysis can proceed.

The third step is to identify the traffic volume that occurs during the same period previously identified (i.e., the period of highest pedestrian demand). Then, convert both the pedestrian and vehicular volumes to hourly flow rates and consult the figure (i.e., Figures 3–6) that most closely relates to the width of the roadway being crossed.

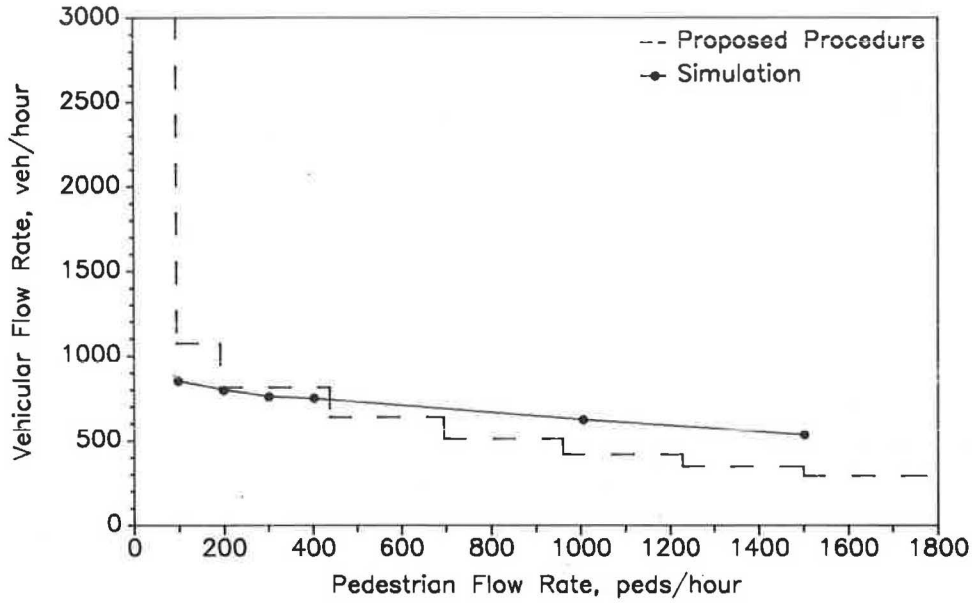

FIGURE 7 Procedure versus simulation results.

The last step is to find where the combination of flow rates intersect on the appropriate figure and determine the suggested traffic control for that location.

Other Considerations

Although this procedure is based on the assumption of random arrivals in the vehicular stream, this procedure can still be applied to streets with platooned arrivals. In general, platooned flows have longer, although less frequent, gaps for pedestrians to use. In most instances, these flows result in more opportunities for pedestrians to cross than would be suggested by an analysis based on random arrivals (*9*). As a result, the proposed procedure can also be used to determine traffic control needs on streets with vehicular progression—as long as it is recognized that the analysis is conservative.

Because the assumption of random arrivals is conservative, field studies are not necessary when the procedure indicates that no control is needed. Similarly, high vehicular and pedestrian volume combinations that fall well within the warrant region (i.e., region 3) would not justify a field study regardless of arrival distribution. The only time a field study should be considered is when the volume combinations just satisfy the proposed warrant for traffic control (based on an inadequate number of gaps) and it is known that the traffic stream has platooned arrivals. Under these circumstances, it is possible that an adequate number of traffic gaps are available in the platooned arrivals and that control is still not needed.

At locations where traffic signals exist within 300 ft along the street to be crossed, the relocation of the pedestrian crossing to the existing traffic signal should be considered before a pedestrian crossing is installed. If a traffic signal is recommended by this procedure, locating the signal at the nearest unsignalized intersection is preferred over a midblock location.

CONCLUSIONS

The purpose of this paper was to develop a procedure for selecting traffic signal control at school crossings. This procedure was developed to supplement and extend the procedure recommended by the MUTCD—Traffic Signal Warrant No. 4. Extensions to the MUTCD procedure include (a) the minimum daily pedestrian volume and flow rate criteria, and (b) a procedure for determining when pedestrian volumes are so high that they must be regulated to improve traffic flow.

The procedure presented in this paper is based on the current MUTCD warrant criteria for traffic control at school crossings. The ITE procedure used in evaluating this warrant requires field studies of pedestrian demand and traffic gap distribution, both of which can be time-consuming and expensive to conduct. In contrast, the proposed procedure eliminates the need for these complex field studies by using a probabilistic approach based on reasonable assumptions of vehicular and pedestrian arrival distributions. By using this procedure as a screening tool, local jurisdictions will be able to evaluate proposed school crossings in the office and eliminate those that would not satisfy the MUTCD warrant. This will enable jurisdictions to more efficiently allocate limited resources to other safety improvement programs by reducing the need for field study to just the "borderline" cases.

This paper has described the theoretical basis of the proposed procedure. Unfortunately, field verification and comparative assessment with the ITE procedure are beyond the scope of this paper. However, limited use with the proposed

procedure combined with simulation results, indicate that the procedure will consistently yield results that limit pedestrian delays.

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