

Pedestrian Delay and Pedestrian Signal Warrants

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Previously determined analytical relations are applied to compute the expected pedestrian delay from the pedestrian signal warrant in the current Manual on Uniform Traffic Control Devices.

A traffic signal warrant can be a set of specifications that define the boundary between two regions. In one of these regions, the installation of signal control will lead to better service for that portion of the traffic stream that is of interest. In the other regions, the converse will also hold true. The concept of better service manifests itself by reducing the average or maximum delay: a reduction in the probability of stops or a reduction in accident potential. This paper is concerned with using pedestrian delay as the boundary criterion in traffic signal warrants.

CURRENT PEDESTRIAN WARRANT

The following traffic signal warrant in the Manual on Uniform Traffic Control Devices (MUTCD) (7) is based on pedestrian demand:

For each hour in an 8-h period, a minimum of 150 pedestrians, in any one crosswalk, must cross a traffic stream that has a minimum of 600 vehicles/h in an undivided roadway, or 1000 vehicles/h in a divided roadway. These values can be reduced by 30 percent if the 85th percentile speed exceeds 65 km/h (40 mph) or if the location lies within the area that is built up in an isolated community that has a population of less than 10 000.

The 1954 revisions to the 1948 edition of the MUTCD specified a total of 250 pedestrians/h (i.e., independent of the number of crosswalks) who must oppose 600 vehicles/h. There was no difference in this value for divided highways. The mean speed of traffic had to exceed 24 km/h (15 mph). As defined for rural areas, these values could be reduced by 50 percent if the average approach speed exceeded 49 km/h (30 mph). Furthermore, the 1954 set of warrants allowed pedestrians to be added, on a one-to-one basis, to the cross-street volume, which was required for qualification under the interruption of continuous traffic warrant. Thus, signals could be justified if, for urban areas with an average approach speed of 32 km/h (20 mph), there were 75 units (pedestrians and vehicles) crossing a main street that has a 750-vehicle volume. For rural conditions and approach speeds exceeding 57 km/h (35 mph), the corresponding minimum values were 50 units and a street with a 500-vehicle volume.

The 1948 edition of the MUTCD specified the same numerical values. However, these values were determined on the basis of the average volume over any 8-h period instead of being determined for each hour in an 8-h period. For the 1954 version, these values are equivalent to a de facto increase of approximately 14 percent in required minimum volumes (2), which is relative to the 1948 version.

As indicated, the pedestrian warrant has required higher volumes over the years. Not unexpectedly, this increase has reduced the applicability of the pedestrian warrant. From a survey of current practices (3), it was found that, out of a total of 12 780 traffic signal in-

stallations made by the responding jurisdictions, only 171 or 1.3 percent were justified by the pedestrian volume warrant. The pedestrian component of the traffic stream was also considered, and it entered into the 506 (4.0 percent) new signals justified under the school crossing warrant. Some consideration of pedestrians may have also entered into the 1243 (9.7 percent) signal installations under the combination warrant.

Previously developed analytical formulations, based mainly on the queuing theory, were used to develop the delay implications of the current pedestrian warrant and the possible warrant formulations that are based on reasonable threshold values for delay.

ANALYTICAL MODEL

The main rationale underlying a pedestrian warrant is to determine those traffic flow conditions that are characterized by inadequate gaps in the traffic stream that affect the safe passage of pedestrians. This rationale implies a concomitant reasonable threshold of delay for pedestrians. If this threshold is violated, then it is necessary to introduce traffic control devices that create a sufficient number of adequate gaps artificially. These traffic control devices (primarily traffic signals) will, in turn, generate vehicle delay, which must be related to the time savings afforded the pedestrians. The initial analysis is made in terms of an isolated, midblock crossing so that confounding, due to change in delay of cross-street vehicle traffic, can be eliminated.

The primary theoretical analysis of pedestrian delay was made by Tanner (4). Tanner used an exponential arrival distribution that was justified for an isolated location to derive the following formulation for the delay of a randomly arriving pedestrian:

$$P(T) = \sum_{s=0}^{r+1} [(-1)^s e^{-sNI} N^s (T - sI + I)^s] / s! + \sum_{s=1}^{r+1} [(-1)^s e^{-sNI} N^{s-1} (T - sI + I)^{s-1}] / (s-1)! \quad (1)$$

where

$P(T)$ = probability (delay > T),
 I = required gap,
 N = vehicles arriving per unit time, and
 r = largest integer $\leq T/I$.

Figure 1 shows the mean of this distribution, which is a function of volume, for the various values of I . As given by Tanner (4), this mean has been calculated from

$$E(D) = (e^{NI} - NI - 1) / N \quad (2)$$

Tanner checked this formulation against field data, and it can be used at the 0.05 level except for extremely small values of T . Tanner attributes this exception to pedestrians' disinclination to immediately accept otherwise satisfactory lags.

ANALYSIS OF CURRENT PEDESTRIAN WARRANT

A rational pedestrian warrant should be based on the following considerations:

1. An acceptable level of average pedestrian delay;
2. A tolerable level of maximum, i.e., 95th percentile, pedestrian delay; and
3. An equitable allocation of total delay between the pedestrian and vehicle components of the traffic stream.

Before proceeding to the development of a suggested pedestrian warrant, one must analyze the current pedestrian warrant in light of the above criteria.

As given in the MUTCD (1), Figure 2 shows $P(T)$ for the following typical conditions:

1. Vehicle volume = 600 vehicles/h;
2. Pedestrian walking speed = 1 m/s (3.5 ft/s); and
3. Street width = 12 m (40 ft).

For an isolated and uncontrolled location that is under

Figure 1. Mean pedestrian delay.

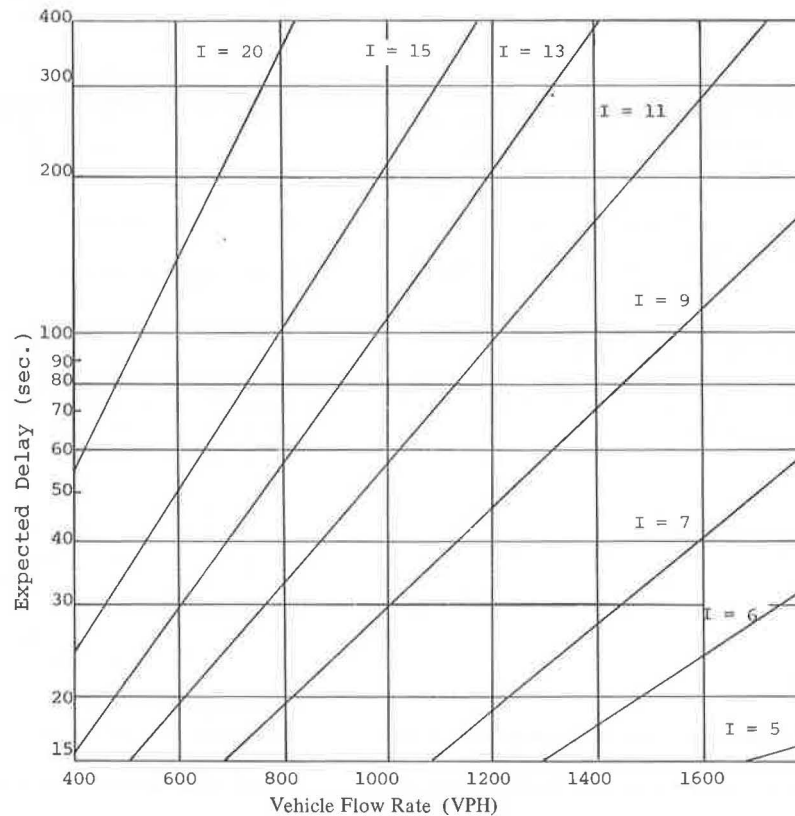
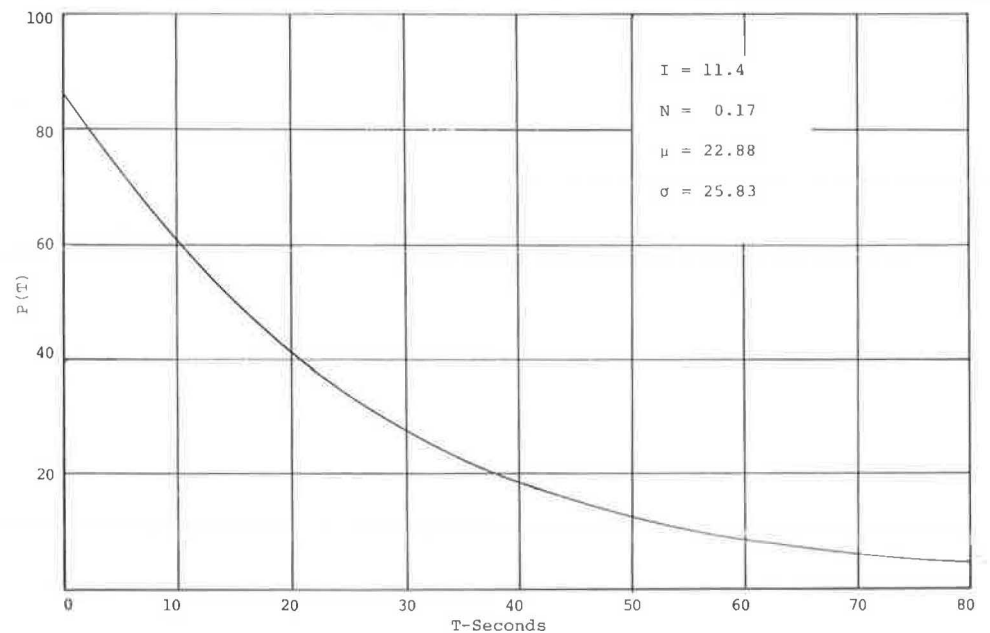


Figure 2. Pedestrian delay probability.



the assumption of exponential arrivals, the mean delay for each arriving pedestrian is 22.9 s. Since this approach accounts only for a single pedestrian, the analysis must be extended to consider a number of pedestrians. For a pedestrian volume of 150/h, the pedestrian accumulation during the mean waiting time of 22.9 s, under the assumption of Poisson arrival, will exceed 5 only 0.1 percent of the time. Since 5 or more pedestrians can easily cross abreast, no additional gap is required. Heavier pedestrian volume, nonrandom arrival, or group arrival may change this situation.

The current warrant conditions of 600 vehicles and 150 pedestrians imply a total pedestrian delay, in the absence of signal control, of 57.2 person-min/h. Long delays to pedestrians will accrue as follows: for a delay of >45 s, 23 pedestrians/h; >60 s, 13 pedestrians/h; and >80 s, 6 pedestrians/h.

For the specific case analyzed, that is, a 12.2-m (40-ft) road and a 1.1-m/s (3.5-ft/s) walking speed, the existing warrant is shown to be equivalent to a mean pedestrian delay of 22.9 s and a 95th percentile delay of 75 s. After a signal is installed, these delay times become a function of the cycle length and split. For a 60-s cycle with a 5-s walking interval, the average pedestrian delay is approximately 25.2 s, and the 95th percentile pedestrian delay is approximately 52 s.

The condition of equalizing delay between pedestrians and passengers in vehicles was analyzed to investigate the validity of adopting this condition as a criterion for specifying a pedestrian warrant. It was found that, for all vehicle flow rates below the saturation level, the average pedestrian delay without signals was always higher than the average vehicle delay with signals. Furthermore, the criterion itself is suspect. Since the pedestrians are exposed to the elements, it is unreasonable to subject them to the same levels of delay as those who are comfortably ensconced in vehicles. Consequently, this criterion was eliminated.

DEVELOPMENT OF PROPOSED PEDESTRIAN WARRANT

For purposes of developing a pedestrian warrant, we selected 30 s as an acceptable level of mean pedestrian delay and 60 s as a tolerable level of maximum (i.e., 95th percentile) delay. The selection of the 95th percentile value as tolerable (rather than the 85th percentile) reflects the exposure of pedestrians to the elements, their relatively unpredictable behavior, and the pedestrians' exposure to accidents of increased severity. These values are suggested on the basis of a review of literature (5,6).

Three different possible behavior patterns can be postulated for pedestrians crossing a bidirectional roadway:

1. The pedestrian crosses whenever he or she perceives an acceptable gap in both directions of travel;
2. The pedestrian crosses whenever he or she perceives an acceptable gap in the near stream of traffic, which is in anticipation of a subsequent acceptable gap in the far stream; and
3. The pedestrian crosses whenever he or she perceives an acceptable gap in the near stream of traffic and waits on the median of the divided roadway for an acceptable gap in the far stream.

Patterns 1 and 2 apply to undivided highways. Based on field observations, Tanner concluded that pattern 1 appeared more frequently than pattern 2. Pattern 3 is common for divided highways when the median provides an adequate refuge.

Figure 3 shows the computed mean pedestrian delay contours for various vehicle flow rates and values of acceptable gaps. If the pedestrian walking speed is 1.1 m/s (3.5 ft/s) and a single lane is assumed to be 3.7 m (12 ft) wide, then the following combinations will yield an average pedestrian delay of 30 s.

| Number of Lanes | Divided Roadways | Total Vehicle Flow | Number of Lanes | Divided Roadways | Total Vehicle Flow |
|-----------------|------------------|--------------------|-----------------|------------------|--------------------|
| 2 | No | 1440 | 4 | Yes | 2080 |
| 3 | No | 800 | 6 | Yes | 1100 |
| 4 | No | 525 | | | |

The second warrant criterion postulated states that the 95th percentile delay to pedestrians should not exceed 60 s. This delay can be computed by using Equation 1. A slight complication is introduced in the case of divided roadways. Although the mean pedestrian delay for divided highways is twice the mean delay for each roadway, assuming a 50-50 directional split, the same methodology cannot be used in determining the percentile points of the distribution. The distribution of pedestrian crossing times for a divided roadway is the sum of the two individual distributions. Since these distributions are identical, the joint distribution is the convolution of the crossing distribution with itself. Figure 4 shows the 95th percentile of pedestrian delay for both divided and undivided roadways as a function of vehicle volume (Q_v) and acceptable gap size (I). Note that the values of I and Q_v for the divided highway case apply for a single roadway. From this value the following table that gives the various combinations for a 95th percentile delay of 60 s has been constructed.

| Number of Lanes | Divided Roadways | Total Vehicle Flow | Number of Lanes | Divided Roadways | Total Vehicle Flow |
|-----------------|------------------|--------------------|-----------------|------------------|--------------------|
| 2 | No | 1160 | 4 | Yes | 1860 |
| 3 | No | 625 | 6 | Yes | 960 |
| 4 | No | 390 | | | |

Figure 5 shows the application of a 30-s mean pedestrian delay and a tolerable 60-s pedestrian delay (95th percentile).

It can be seen that the criterion of tolerable pedestrian delay governs throughout. This criterion is independent of pedestrian volume (Q_p). Since the use of signals would not be considered at extremely low pedestrian flow levels, a lower limit of pedestrian hourly demand must be set. The current MUTCD sets this figure at 150 pedestrians/h. Box (5) based his derivation on a proposed Canadian warrant and suggested a minimum of 60 pedestrians/h, as long as these pedestrians incur a total delay of 1.0 h. The pedestrian flows that produce a total delay of 1.0 h were determined from Equation 2 and are plotted in Figure 6.

A minimum volume of 90 pedestrians/h was suggested in a proposed pedestrian signal warrant in Ireland (6). The current MUTCD implies in the interruption of continuous traffic warrant that delay to 100 or more traffic units/h may justify signals. It is, therefore, suggested that a proposed pedestrian warrant be subject to two different lower bounds: (a) an aggregate pedestrian delay of 1 h/h and (b) a minimum pedestrian volume of 100/h.

PROPOSED PEDESTRIAN WARRANT

A proposed pedestrian warrant for the undivided highway case is shown in Figure 7. The graph shows the measured value of traffic flow and the required value

for an accepted gap (I). When approach speeds exceed 64 km/h (40 mph), the required value of I should be increased by 1 s to reflect the increased difficulty in identifying an appropriate gap. The accepted gap (I) is the time necessary to cross the roadway at the prevailing pedestrian walking speed. This speed is generally between 0.9 and 1.2 m/s (3.0 and 4.0 ft/s) in the United

States (7); however, values as high as 1.5 m/s (5 ft/s) are used in other areas (8).

The minimum pedestrian volume that warrants a signal is read, and, if the actual pedestrian volume exceeds this value, a signal is warranted. The W-scale, which is also shown in Figure 7, can be used if a walking speed of 1 m/s (3.5 ft/s) is assumed. This warrant

Figure 3. Mean pedestrian delay contours.

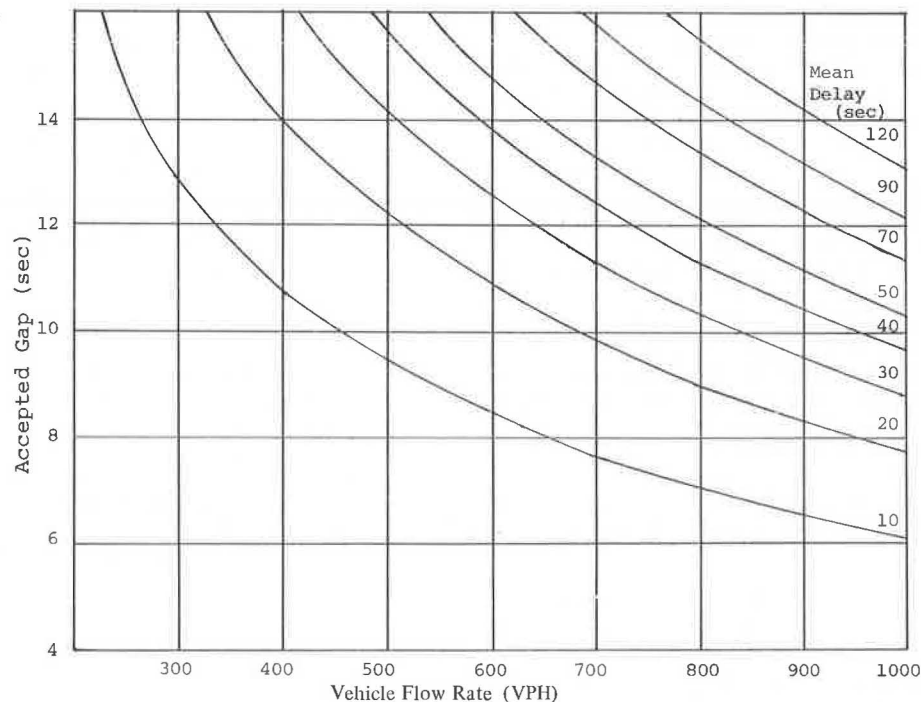
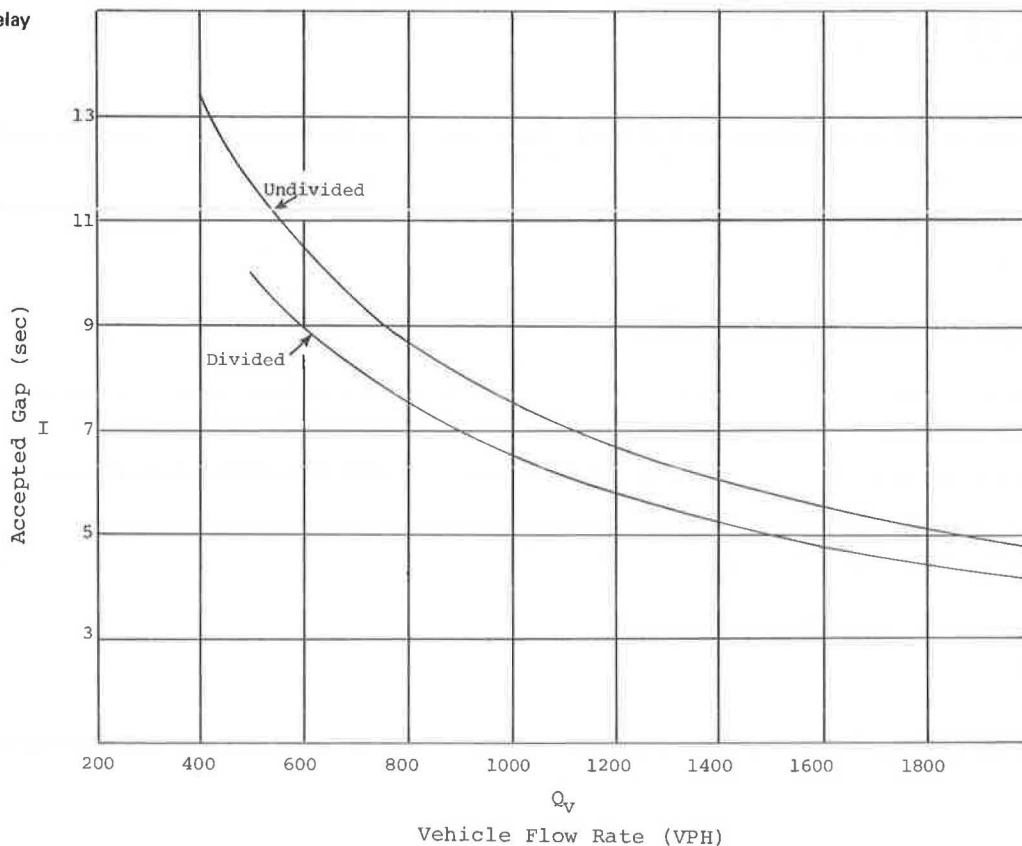


Figure 4. 95th percentile of delay distribution.



curve was constructed by superimposing the 95th percentile delay curve that applies for hourly pedestrian volumes exceeding 200 and the 1-h aggregate delay curves for lower pedestrian volumes.

The curves shown in Figure 8 apply to divided highways. These curves are based on the assumption of approximately equal directional traffic volume split and do not apply for the case in which the split is markedly un-

balanced. For the purposes of this warrant, a divided highway is defined as one with a center median (either curbed or painted) that is wide enough to accommodate the maximum (i.e., 95th percentile) pedestrian platoon. If these curves for the specification of the pedestrian signal warrant are to be applied, a lower bound of 500 and 1000 vehicles/h for undivided highways and divided highways respectively has been used.

Figure 5. Two pedestrian warrant criteria.

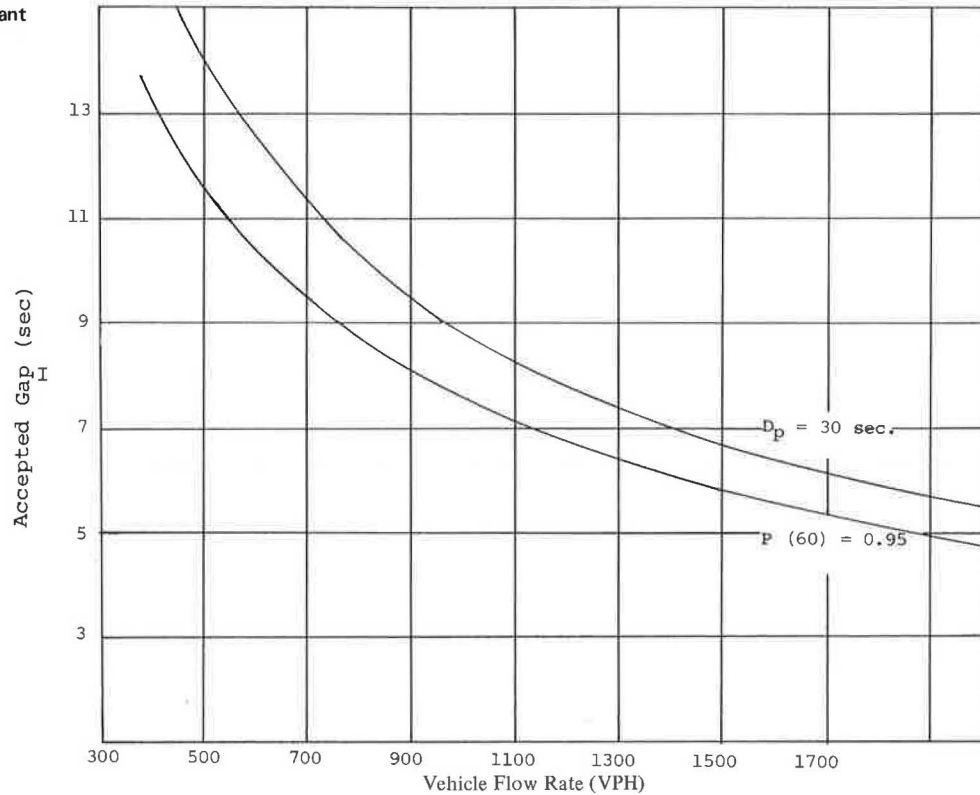
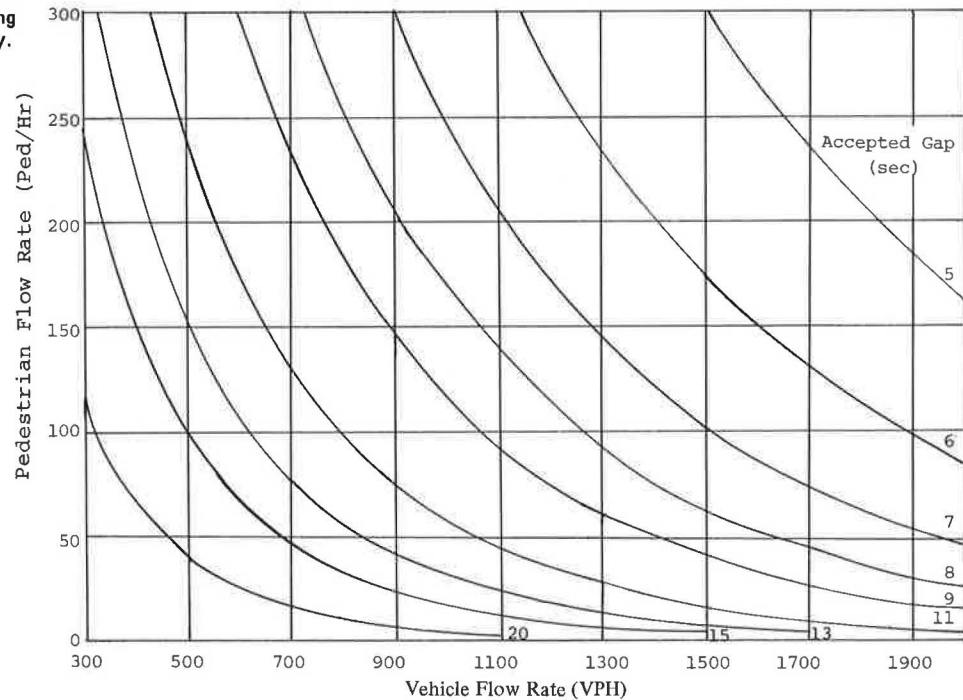


Figure 6. Volume levels producing 1.0 h/h aggregate pedestrian delay.



DISCUSSION OF WARRANTS

Thus far, the analysis has addressed the pedestrian delay that has occurred while pedestrians wait for acceptable gaps in traffic. However, by a strict interpretation of Chapter 11, Article V of the Uniform Vehicle Code (9), a pedestrian may force an adequate gap in traffic at any unsignalized intersection or marked mid-block crosswalk as long as a minimum, natural gap that is sufficient for a driver to yield or stop occurs. In certain jurisdictions such as California, this rule is strictly interpreted. The result of such a rule will be the acceptance of much shorter gaps by pedestrians,

thus reducing the nonsignalized pedestrian delay.

This phenomenon of preemption by pedestrians has led to the adoption of maximum pedestrian volume criteria in those jurisdictions such as the United Kingdom where some type of pedestrian priority rule is in effect at designated crossings. It has been found that signals can be justified at volumes in excess of 360 pedestrians/h to reduce vehicle delay (10).

The explicit assumptions of isolated intersections (i.e., random arrivals) at a midblock pedestrian location should be kept in mind when evaluating these proposed warrants. Although the proposed warrant applies to this set of conditions, it can be extended, in general,

Figure 7. Proposed pedestrian signal warrant for an undivided highway.

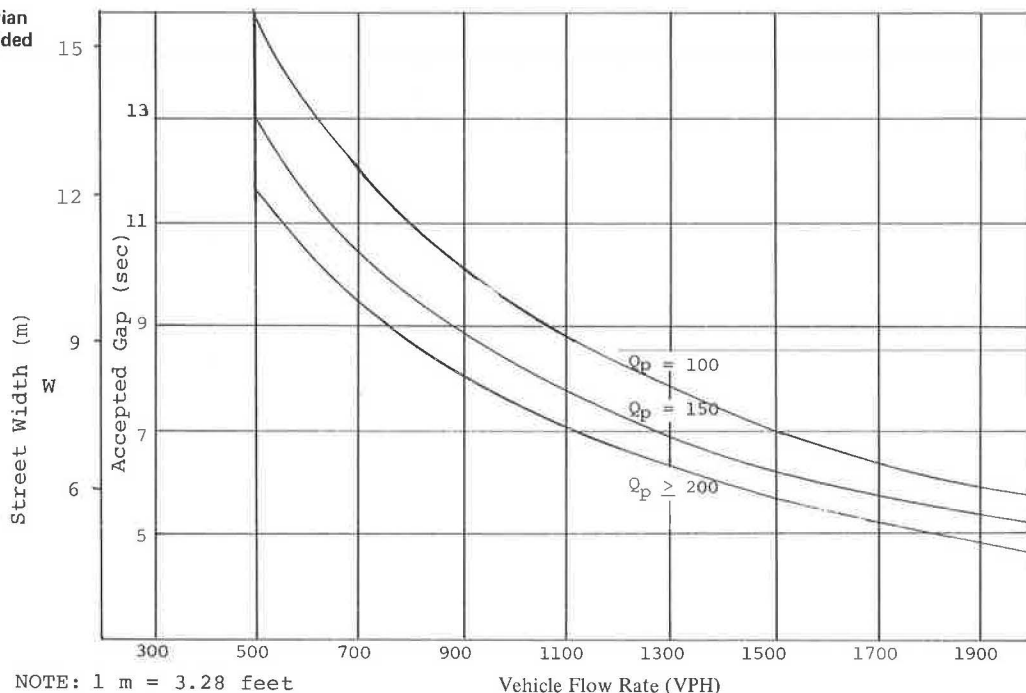
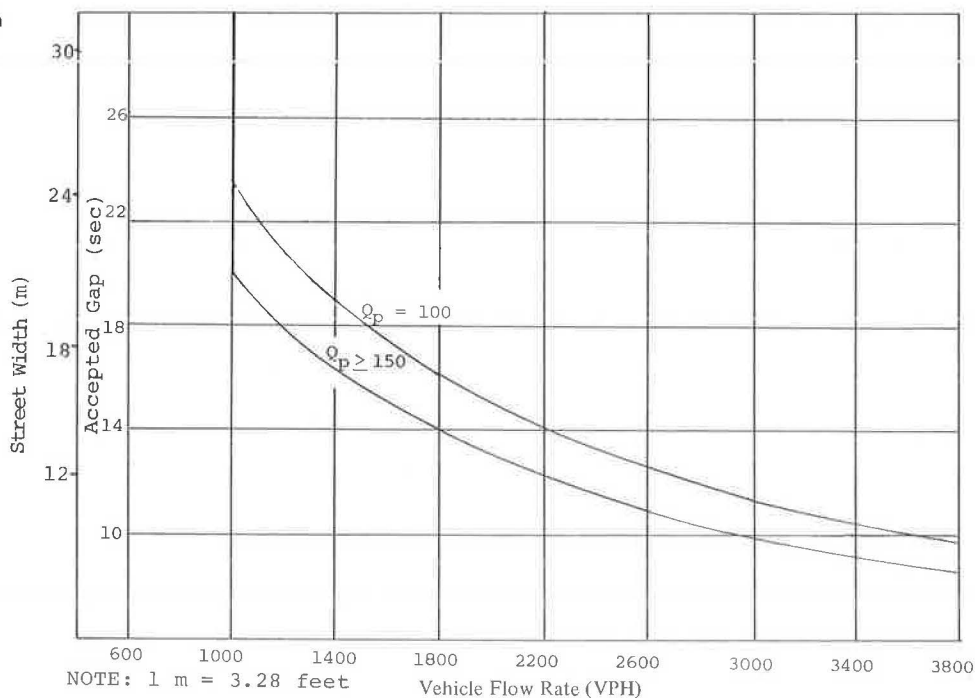


Figure 8. Proposed pedestrian signal warrant for a divided highway.



to crosswalks at intersections. Tolerable pedestrian delay is the prime criterion on which the proposed warrant is based, and such delay is essentially independent of the crosswalk location. It is recognized that at an intersection a pedestrian must contend not only with cross traffic but also with turning vehicles. Those vehicles turning from the cross streets will be few in number; however, since these intersections require a signal, they will have failed to satisfy the warrants for vehicle volume.

The numerical warrants for both midblock and intersection locations are presented in Figures 7 and 8. Before signals are installed, these warrants should be met or exceeded for 4 h on an average weekday. Alternatively, the warrant could be met or exceeded for 10 h on any weekend if at least 3 h are on the day with lighter volumes. These periods have been selected to correspond to those used for other warrants developed (3) and reflect the typical peaking characteristics of urban traffic.

All signals installed under this warrant should be provided with pedestrian signal heads and pedestrian push-button detectors. Normally these signals should not be flashed. If installed at an intersection location, the installation should be at least semiactuated for side-street traffic. A pedestrian signal installed at an intersection and meeting only the weekend requirements should be fully actuated.

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ciation of State Highway and Transportation Officials, or the individual states participating in the National Cooperative Highway Research Program.

REFERENCES

1. Manual on Uniform Traffic Control Devices for Streets and Highways. Federal Highway Administration, U.S. Department of Transportation, 1971.
2. L. J. Pignataro. Traffic Engineering Theory and Practice. Prentice-Hall, Englewood Cliffs, N.J., 1973.
3. E. Lieberman, G. F. King, and R. Goldblatt. Traffic Signal Warrants. KLD Associates, Inc., Huntington Station, N.Y., 1976; Final Rept., NCHRP Project 3-20(1).
4. J. C. Tanner. The Delay to Pedestrians Crossing a Road. *Biometrika*, Vol. 38, 1951, pp. 382-392.
5. P. C. Box and W. A. Alroth. Assembly Analysis and Application of Data on Warrants for Traffic Control Signals. Prepared for the Signal Committee, National Joint Committee on Uniform Traffic Control Devices, unpublished, March 1967.
6. F. Simons. Warrants for the Installation of Pedestrian Crossing Facilities. The National Institute for Physical Planning and Construction Research, Dublin, Ireland, 1970.
7. J. E. Baerwald, ed. Transportation and Traffic Engineering Handbook. Prentice-Hall, Englewood Cliffs, N.J., 1976.
8. Research on Road Safety. Department of Scientific and Industrial Research, Her Majesty's Stationery Office, London, 1963.
9. Uniform Vehicle Code. National Committee on Uniform Traffic Laws and Ordinances, Washington, D.C., 1968.
10. R. T. Underwood. Tentative Warrants for the Installation of Pedestrian Crossings. Victoria County Roads Board, Res. Memo. 13, 1957.

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Knowledge and Perceptions of Young Pedestrians

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The progress of a research study on school-age pedestrians has been previously reported in a paper that dealt with the behavior of drivers in relation to the existing signing at four school sites in three states. That research study has now been completed, and this paper deals primarily with the findings regarding youngsters in the 5 to 14-year-old age group. Data are provided on the accident experience of the young pedestrians and on their behavior, attitudes, and knowledge. Students in sections of the eastern United States were observed walking to school and were then surveyed on their pedestrian behavior and knowledge. Significant differences by age groupings were noted for both the accident data and knowledge responses.

This paper describes a school walking-trip study that was undertaken during the summer of 1973 and completed in the spring of 1975 with the publication of a walking-trip guidebook. The study objective was to develop guidelines for the protection of young pedestrians (ages 5 to 14 years) walking to and from school. These guidelines were based on field surveys of the young pedestrian and the driver regarding designated school zones and specific school-crossing protective devices. The guidelines are described in detail in a companion report (1).