Development of Improved Pedestrian Warrant for Traffic Signals

CHARLES V. ZEGEER, SNEHAMAY KHASNABIS, AND JOHN C. FEGAN

The 1978 version of the Manual of Uniform Traffic Control Devices (MUTCD) specifies a total of eight traffic signal warrants, and one of these is the minimum pedestrian volume warrant. Many traffic engineers and researchers have argued that the minimum pedestrian volume is inappropriate, in that an inordinately large pedestrian volume is required over an extended period (150 pedestrians/h for 8 h during a 24-h day on the highest volume crosswalk). As a result, most of the pedestrian signals installed in the United States today are based largely on the intuitive judgment of traffic engineers. The purpose of this paper is to (a) conduct an in-depth review of the current MUTCD pedestrian volume warrant and other recommended warrants reported in the literature and from other countries, and (b) develop and recommend a revised pedestrian signal warrant that might lend itself to better practical application. Five criteria were used in evaluating the MUTCD pedestrian warrant, and the review generally indicated that the current warrant is inappropriate for most real-world situations. A revised warrant was developed based on an analysis of pedestrian volume distributions in a number of U.S. cities and a branching analysis of pedestrian accident and volume data. The warrant requires minimum hourly pedestrian volumes on an average day of 60 or more (for each of any 4 h), 90 or more (for each of any 2 h), or 110 or more (during the peak hour). The number of adequate gaps in the traffic stream should also be less than 60/h during the same period when the pedestrian volume criterion is satisfied.

The 1978 version of the Manual of Uniform Traffic Control Devices (MUTCD) specifies eight warrants for the installation of a traffic signal. Of the eight warrants, warrant 3 (minimum pedestrian volume) and warrant 4 (school crossing) are most related to pedestrians. According to MUTCD, pedestrian signal indications (i.e., WALK/DON'T WALK signals) shall be provided when a traffic signal is installed under the pedestrian volume or school crossing warrant (1). Warrants 6 (accident experience) and 8 (combination of warrants) also allow for some consideration to pedestrians. In addition, MUTCD requires pedestrian signal indications (a) when an exclusive pedestrian phase is provided, (b) when vehicular signal indications are not visible to pedestrians, and (c) at signalized school crossing intersections.

Also, MUTCD suggests that pedestrian signal indications may be installed when (a) a pedestrian signal is needed to minimize vehicle-pedestrian conflicts or to assist pedestrians in making a safe crossing, (b) multiphase indications may confuse pedestrians, and (c) a divided roadway exists and the signal timing only allows pedestrians to cross to the island during one interval.

Note that two separate issues must be addressed, including (a) warrants for installing new traffic signals (with pedestrian signal indications) based on pedestrian considerations, as provided in warrant 3 (minimum pedestrian volume) and warrant 4 (school crossing), and (b) warrants for installing new pedestrian signal indications (i.e., WALK/DON'T WALK signals) where traffic signals already exist. This study focuses primarily on the former issue, that is, warrants for installing new traffic signals, particularly as they relate to the minimum pedestrian volume warrant (warrant 3).

The basic minimum pedestrian volume warrant requires 600 vehicles/h entering the intersection (both approaches of the major street) for each of any 8 h of an average day and also 150 or more pedestrians/h during the same period on the highest-volume crosswalk. Many traffic engineers and researchers have argued that the current MUTCD pedestrian volume warrant is inappropriate. Pedestrian volume requirements are considered too high by most traffic experts to have any practical applications. In order to provide pedestrian signalization, many traffic engineers must rely on their own engineering judgment when selecting locations for pedestrian signal installations. This has created inconsistencies between regions of the country and often between state and local agencies concerning the conditions under which pedestrian signals are installed.

The purpose of this paper is to review and critique the existing MUTCD warrant and other relevant guidelines reported in the literature and to recommend a revised warrant more suitable for practical application in the United States. The work reported in this paper was conducted as a part of a Federal Highway Administration (FHWA) sponsored study on pedestrian signalization alternatives, which is currently in the final stages of completion.

REVIEW OF EXISTING AND PROPOSED WARRANTS

A review of the pedestrian volume warrant included conducting a comprehensive literature review to find other studies that have been conducted relative to this warrant. In particular, studies that provided other recommended warrants to replace the current MUTCD one were analyzed to determine their validity. A critical analysis of the MUTCD warrant and the other proposed pedestrian volume warrants was helpful in the development of recommended warrants. This review is presented below.

The 1978 MUTCD warrant for minimum pedestrian volume (warrant 3) is satisfied when 600 or more vehicles/h enter an intersection (both approaches of the major street) for each of any 8 h of an average day along with 150 or more pedestrians/h during the same period crossing the highest-volume crosswalk crossing the major street. For a divided highway, 1000 or more vehicles/h are required. Where the traffic speed exceeds 40 mph or in isolated communities (less than 10 000 population), the requirements are only 70 percent of those stated above. At mid-block locations, the warrants are the same, provided that the crosswalk is not closer than 150 ft to another established crosswalk (1).

In 1967, a study was conducted by Box for the signal committee of the National Joint Committee on Uniform Traffic Control Devices (2). The purpose of the study was to review warrants for traffic signals and suggest considerations and numerical values for warrants. The warrant recommended in this study requires a minimum of 60 pedestrians/h for 1 h (or for two 30-min periods) and also an average of 60 s of mean delay per pedestrian for one of the two 30-min periods. This warrant is based on the premise that pedestrians are subjected to greater exposure to injury compared with motor vehicles, and motorists have the added protection from inclement weather.

A study was conducted in 1976 for the National Cooperative Highway Research Program (NCHRP) entitled Traffic Signal Warrants (3). The warrant is based primarily on pedestrian delay considerations and is presented in graphical form for undivided and divided streets. A minimum of 100 pedestrians/h is required to meet this warrant. Minimum required traffic volumes for undivided and divided streets are 500 and 1000 vehicles/h, respectively (3).

A delay-based warrant was presented by King in 1977 (4) that uses an exponential arrival distribution model originally developed by Tanner in 1951 (5). Based on a 30-s assumed acceptable level of pedestrian delay and a 60-s level of maximum tolerable pedestrian delay, pedestrian signal warrants were prepared graphically for undivided and divided highways. It should be noted that Tanner's delay model is based on the assumption of random arrival of vehicles, whereas vehicular arrivals in most urban intersections are not likely to be random in nature. Thus, the validity of using the Tanner delay model for developing warrants at urban intersections may be questioned.

The Canadian traffic signal installation warrant developed in 1966 is based on pedestrian volumes and delays. The specific warrant is as follows (6):

> a. Pedestrians on an average must wait in excess of 60 seconds before being able to cross the main street in safety;
> b. The number of pedestrians wishing to cross is at least 60 per hour;
> c. The conditions specified in (a) and (b) exist for any four not necessarily continuous hours of a normal day;
> d. The intersection or other location is suitable for signalization; and
> e. The nearest existing or proposed signal installation is more than 1000 feet away.
>
> The existing delay occasioned to pedestrians should be determined by a study at the location in question.

The Canadian warrants are similar to the warrants recommended by Box (2) in terms of the minimum required pedestrian volumes (60/h) and mean delay per pedestrian (60 s). However, the Canadian warrant requires those conditions for 4 h, compared with two 30-min periods in the Box-recommended warrants.

As a part of the FHWA-sponsored study from which this paper originates, we also reviewed pedestrian signal warrants in a number of other countries, including those in Great Britain, Ireland, Australia, and New Zealand. This review revealed a considerable amount of variation in the pedestrian volume (ranging between 90 and 600 pedestrians/h) for warranting a signal.

CRITIQUE OF MUTCD WARRANT

In order to evaluate the existing pedestrian signal warrant, five specific criteria were selected, as follows:

Criterion 1: appropriateness and reasonableness of the warrant,
Criterion 2: complexity of the warrant,
Criterion 3: data requirements,
Criterion 4: flexibility of the warrant, and
Criterion 5: acceptability of the warrant by practicing traffic engineers in the United States.

The intent of criteria 1 is to see if this warrant is realistic in terms of how many locations are likely to meet the warrant under real-world conditions. Criteria 2 is designed to test the amount of time and expertise needed to apply the warrant. Criteria 3 is on the data burden associated with the warrant, and criteria 4 is designed to answer the question if it can account for most of the real-world situations or if it offers ways to reduce required data-collection efforts or simplify the analysis procedure. Last, criteria 5 is somewhat a combination of the preceeding four but is important in its own right, since the traffic engineering community is ultimately responsible for using the warrants to install signals.

As a pedestrian signal warrant is tested by using each of the criteria, a rating of excellent, good, fair, or poor was assigned, depending on how well the criteria are satisfied. The assignment of these ratings is largely subjective, but much objective information was used to apply them. Also, it is important to state that not all criteria are of equal importance. For example, the appropriateness of a warrant is certainly the most important criteria, since if the warrant is totally inappropriate (criteria 1), then the other criteria do not really matter.

Criteria 1: Appropriateness and Reasonableness

The 1978 MUTCD pedestrian volume warrant (warrant 3) was evaluated by using the five criteria discussed above. In terms of appropriateness and reasonableness (criterion 1), several sources were used to judge the warrant. Discussions were held with more than 50 traffic engineers throughout the country who overwhelmingly indicated that the current MUTCD pedestrian volume warrant is unrealistically high. In most cities, few or no traffic signals can be justified based on the pedestrian volume warrant. This is confirmed by a survey of current practices in the NCHRP report, which showed that only 171 out of 12 780 traffic signal installations (1.3 percent) were installed based on the pedestrian volume warrant (3). Also, a majority of the available studies that reviewed the pedestrian volume warrant recommended or suggested warrants that were much lower (easier for a signal to be justified) than the MUTCD warrant in terms of required numbers and duration of pedestrian volumes.

To gain further insight into the reasonableness of the MUTCD pedestrian volume warrant, an analysis was conducted of the daily pedestrian volumes that would be required to warrant a pedestrian signal. Pedestrian and traffic volume data were collected from 388 locations from Chicago, Richmond, and Detroit. At each of the sites, 12-h pedestrian counts were obtained from the local agencies. Next, a computer program was used to develop the distribution of the pedestrian volumes from the 1st highest hour to the 12th highest hour.

The highest hourly pedestrian volume (in percent) was found for each location (regardless of when that hour occurred), and the average of the 388 highest hourly pedestrian volumes was 16.5 percent (of the 12-h total volume). The average of the second highest hourly volume was 13.3 percent (of the 12-h volume), and so on, as shown in Table 1. By using data from 24-h pedestrian counts from Seattle (7), it was found that the peak 12-h pedestrian volume (7:00 a.m. to 7:00 p.m.) represented 86 percent of the 24-h pedestrian volume. The percentage volumes were then adjusted to the percentage of the 24-h volumes for the central business district (CBD), the outlying business district (OBD) and fringe areas, residential areas, and all locations combined (Table 1).

It can be seen that, for an average intersection, the eighth highest hourly pedestrian volume would represent about 5.5 percent of the 24-h pedestrian volume. Also, the cumulative total of the highest 8 h of pedestrian volume represents about 70.5 percent (14.2 + 11.4 + ... + 5.5) of the 24-h total (Table 2). A plot of the distribution of pedestrian volume from the 1st to the 12th highest volume hours is shown in Figure 1. One must consider the following information in order to assess the implication of the MUTCD warrant:

Table 1. Distribution of pedestrian volume by the 12 highest hourly volumes.

	CBD Locations (%) (n = 43)		OBD and Fringe Locations (%) (n = 77)		Residential Locations (%) (n = 268)		All Locations (%) (n = 388)	
Hour	12 h	24 h	12 h	24 h	12 h	24 h	12 h	24 h
Highest	18.6	16.0	16.0	13.8	16.4	14.1	16.5	14.2
2nd	14.7	12.6	13.1	11.2	13.2	11.4	13.3	11.4
3rd	11.9	10.2	11.2	9.6	11.2	9.6	11.3	9.7
4th	9.7	8.3	9.8	8.4	9.9	8.5	9.8	8.4
5th	8.8	7.6	8.9	7.7	8.9	7.7	8.9	7.7
6th	7.9	6.8	8.2	7.1	7.9	6.8	8.6	7.4
7th	6.8	5.8	7.3	6.3	7.2	6.2	7.2	6.2
8th	6.0	5.2	6.6	5.7	6.4	5.5	6.4	5.5
9th	5.2	4.5	5.9	5.1	5.8	5.0	5.7	4.9
10th	4.5	3.9	5.3	4.5	5.1	4.4	5.0	4.3
11th	3.6	3.1	4.3	3.7	4.4	3.8	4.3	3.7
12th	2.3	2.0	3.4	2.9	3.6	3.0	3.0	2.6
Total	100.0	86[a]	100.0	86[a]	100.0	86[a]	100.0	86[a]

Note: CBD = central business district, and OBD = outlying business district.

[a]The remaining 14 percent of the daily pedestrian volume occurs during nighttime hours (between 7:00 p.m. and 7:00 a.m.).

Table 2. Summary of minimum hourly volume required.

Hour[a]	Daily 24-h Pedestrian Volume (%)	Minimum Hourly Volume Required to Meet Pedestrian Volume Warrant	Hour[a]	Daily 24-h Pedestrian Volume (%)	Minimum Hourly Volume Required to Meet Pedestrian Volume Warrant
Highest	14.2	387	8th	5.5	150
2nd	11.4	311	9th	4.9	134
3rd	9.7	264	10th	4.3	117
4th	8.4	229	11th	3.7	101
5th	7.7	210	12th	2.6	71
6th	7.4	202	13th-24th	14.0	382
7th	6.2	169	Total[b]		2727

Note: The minimum hourly volume for each row was based on the control total of 150 hourly pedestrians comprising 5.5 percent of the total during the 8th highest hour.

[a]Column gives the Xth highest hourly volume for the hours of the day.
[b]Total of the 24-h volume.

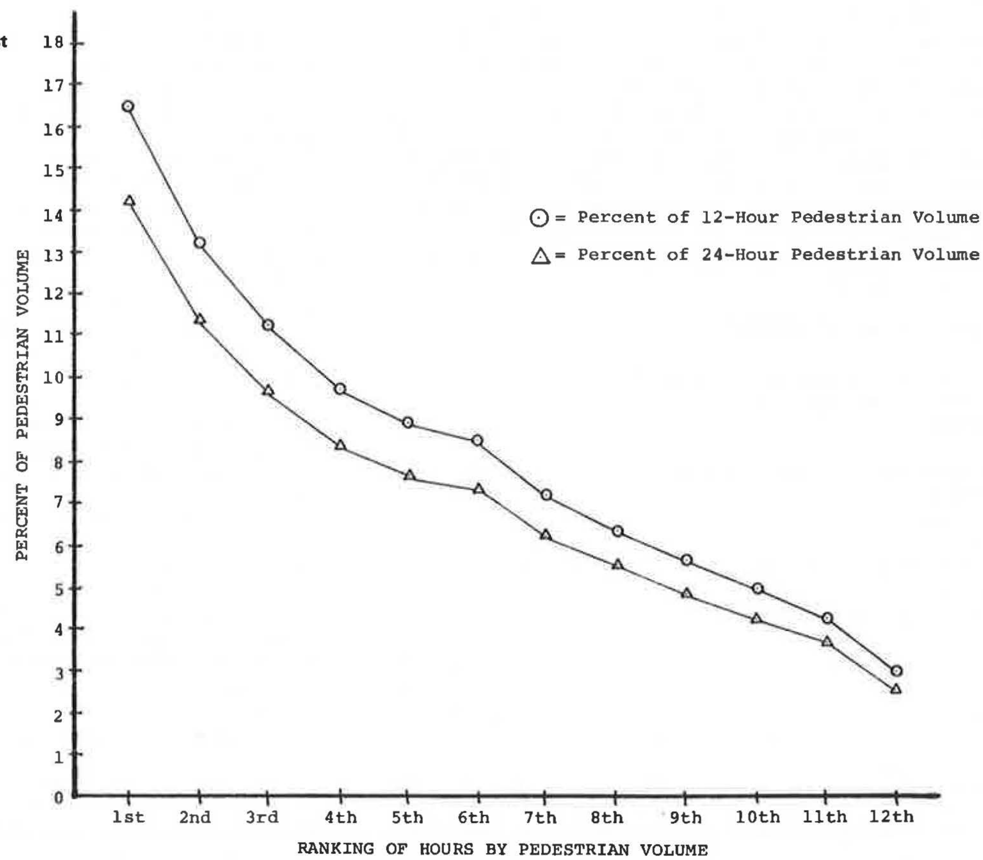

Figure 1. Distribution of pedestrian volume by hour for the first 12 highest hourly volumes.

1. A minimum of 150 pedestrians/h are required on the highest volume approach (which is only one leg of an intersection) for any 8 h of an average day. Thus, the first eight highest hours of an average day must each have at least 150 pedestrians/h, even though that eighth highest hour only represents 5.5 percent of the daily (24-h) pedestrian volume.

2. In order to meet the MUTCD minimum pedestrian volume warrant (150 pedestrians/h for the eighth hour), the pedestrian volumes that correspond to the first seven highest hours can also be computed based on the pedestrian volume distribution given above. For example, if the eighth highest hour requires 150 pedestrians and corresponds to 5.5 percent of the daily traffic, the pedestrian volume for the 1st highest hour (for an urban intersection with an average volume distribution) can be computed as follows:

(14.2 percent/5.5 percent) x 150 = 387 pedestrians in the 1st highest hour (1)

3. Likewise, for the second highest hour (11.4 percent of the daily volume) of the day, the volume is calculated as 311 pedestrians/h. For each of the other time periods, the hourly pedestrian volumes can be computed in a similar fashion. As Table 2 shows, a minimum of about 2727 pedestrians/day is required on the highest volume approach in order to satisfy the minimum pedestrian volume warrant (assuming an average hourly distribution of pedestrian volumes).

4. The next step is to equate the 2727 pedestrians on the highest volume approach to the equivalent total pedestrian volume on all four approaches for an average four-legged intersection. If pedestrian volumes crossing all four approaches were equal, then 25 percent of the pedestrian volume would cross each leg. However, such uniform crossing volumes do not usually exist in the real world. An analysis was conducted of 101 intersections (selected at random from Chicago and Washington, D.C.) to determine what percentage of the volume actually corresponds to the highest-volume leg for a typical four-legged intersection. By computing the percentage of the first, second, third, and fourth highest legs (based on pedestrian volume), the following percentages were found:

Leg Volumes	Mean	Standard Deviation	Percent
Highest	0.360	0.079	36.0
2nd	0.265	0.037	26.5
3rd	0.214	0.0396	21.4
4th	0.161	0.0425	16.1
Total	1.00		

Based on these percentages, the highest-volume crossing represents about 36 percent of the total intersection volume. Note that the standard deviation of each average value is quite low, which indicates low deviation from the mean. Therefore, it is possible to convert the minimum required daily volume of 2727 for the highest-volume leg to an equivalent total intersection volume for an average four-legged intersection, as follows:

2727/0.36 percent = 7575 pedestrians/day (all four approaches of a four-legged intersection) (2)

The equivalent pedestrian volume for a three-legged intersection would be less than 7575. For a midblock crossing, the previously calculated value of 2727 would be the expected minimum daily pedestrian volume that corresponds to the MUTCD minimum pedestrian volume warrant.

The above analysis was conducted to illustrate the high daily volume of pedestrians (about 7600 at

Figure 2. Distribution of pedestrian volume by time of day.

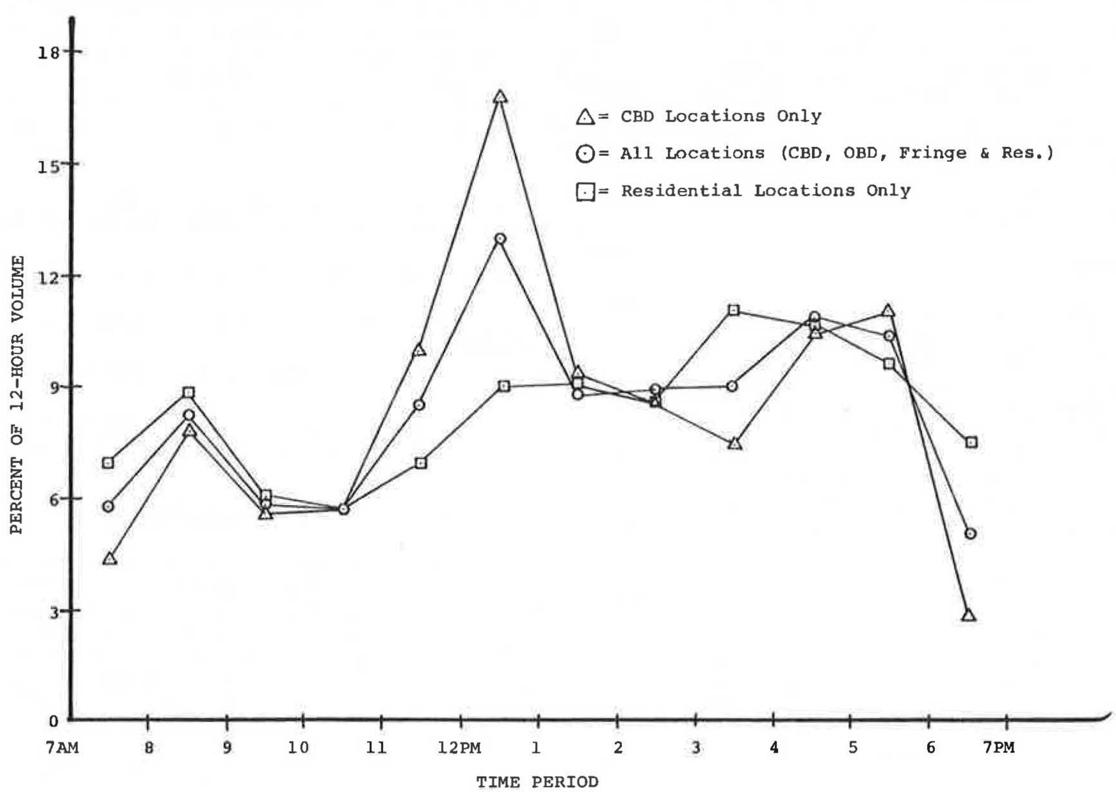

Table 3. Number of intersections meeting various vehicle and pedestrian volume criteria for different data-collection periods.

City	No. of Intersections	Locations Meeting Vehicle Warrant		Locations Meeting Pedestrian Volume Warrant: 60 per Hour, 1 h		2 h		4 h		8 h		100 per Hour, 1 h		2 h	
		No.	Percent	No.	Percent	No.	Percent	No.	Percent	No.	Percent	No.	Percent	No.	Percent
Chicago	236	212	90	217	92	202	86	174	74	136	58	176	75	161	68
Washington	186	143	77	126	68	112	60	80	43	57	31	97	52	81	44
Total	422	355	84	343	81	314	74	254	60	193	46	273	65	242	57

a typical four-legged intersection) that is necessary in order for the minimum pedestrian volume to be met. Such high volumes are quite unrealistic, except in a very small number of locations (such as in large urban areas). A plot of the average pedestrian volumes (in percent) by time of day is shown in Figure 2, as determined from the data base.

To further test the MUTCD warrant for appropriateness and reasonableness, an analysis was conducted to determine the percentage of the traffic-signalized locations that would meet the 8-h MUTCD pedestrian volume warrant in two large urban areas. Chicago and Washington were chosen, since 10-12 h of pedestrian volume data were readily available at intersections in those cities. Of 422 intersections chosen in the two cities, 355 (84 percent) had sufficient vehicle volumes (600/h for 8 h), but only 34 (8 percent) had sufficient pedestrian volumes (150 or more on the highest-volume crosswalk for any 8 h) to meet the warrant. An additional 78 intersections (19 percent) could have met a 4-h pedestrian volume warrant (150/h on highest-volume approach for at least 4 h). A total of 156 of the signalized intersections (37 percent) had sufficient pedestrian volumes for at least 1 h/day. A summary of the data is given in Table 3. It appears that virtually all of the signals in the sample were probably installed based on other signal warrants.

Based on all the available information discussed above, it was determined that the pedestrian volume requirements (150/h on the highest-volume approach for each of 8 h) of the MUTCD minimum pedestrian volume warrant is unrealistically high. It is not appropriate for most cities and should be revised to allow for signal installations at locations with daily pedestrian volumes considerably below the current high requirements. Thus, the MUTCD warrant was rated as poor based on criterion 1.

Criteria 2: Complexity

The pedestrian volume warrant was next evaluated based on criterion 2, which involves the complexity of using a warrant. The warrant is applied by simply reviewing the hourly volumes of pedestrians and vehicles and determining whether eight of those hours meet the criteria. An adjustment of 70 percent is made in these minimums for average traffic speeds more than 40 mph. This is a relatively uncomplicated procedure to use, so the MUTCD minimum pedestrian volume warrant was rated as good based on criterion 2.

Criteria 3: Data Requirements

The data requirements (criterion 3) are somewhat difficult to meet for most cities. In order to find 8 h of volumes that meet the warrants, a city traffic engineer may need to collect volume counts for 8-12 h in a single day, since the peak 8 h may not always be known until the data have been collected. Of the more than 70 major U.S. cities contacted, only Detroit and Chicago were each found to routinely conduct 10- to 12-h pedestrian volume counts. Also, in Washington, D.C., 10-h pedestrian volume counts were available at most signalized intersections. Richmond had more than one hundred 12-h counts, and Seattle had collected some 24-h sidewalk counts with a mechanical counter a few years ago, although peak-hour pedestrian counts are more common. A few cities collected occasional manual counts of 1-3 h. Except for those cities, most of the other cities contacted collected little or no pedestrian volume data.

Based on these findings, it is not realistic to expect cities to use their limited personnel to collect large amounts of additional data in order to use a signal warrant (particularly in the current financial situation, when many city and state agencies are forced to reduce their existing staffs). Therefore, a poor rating was assigned to the MUTCD warrant for criterion 3.

Criteria 4: Flexibility

Criterion 4 involves the flexibility of the warrant in accounting for a range of highway and traffic conditions. The current warrant allows a 70 percent adjustment in the minimum criteria for high-speed locations (greater than 40 mph) or small towns (less than 10 000 population). Also, the minimum traffic volume is 1000 vehicles/h instead of 600 vehicles/h if a raised median exists. However, except for this possible one-time adjustment of 70 percent, the warrant is not adequately sensitive to gaps in traffic or to the following related traffic and highway variables:

1. Traffic speed (i.e., 25 versus 35 mph),
2. Street width (i.e., undivided streets of 20 versus 50 ft),
3. Vehicle volumes (i.e., volumes of 700 versus 2000/h),
4. Vehicle arrival rates (i.e., random versus traffic queues), and
5. Pedestrian walking speeds (2.5 versus 4 ft/s).

Therefore, the MUTCD minimum pedestrian volume warrant was rated as fair/poor according to criterion 4 (flexibility).

Criteria 5: Acceptability by Traffic Engineers

Criterion 5 is the acceptability of the warrant by practicing traffic engineers in the United States. As discussed previously, the current MUTCD minimum pedestrian volume warrant fares poorly in the opinion of many traffic engineers in the United States (based on discussions with traffic engineers in numerous large cities) due to its unrealistically high required pedestrian volume and large amount of required data.

In summary, the following represent the ratings

				150 per Hour							
4 h		8 h		1 h		2 h		4 h		8 h	
No.	Percent	No.	Percent	No.	Percent	No.	Percent	No.	Percent	No.	Percent
126	53	83	35	89	38	63	27	36	15	12	5
61	33	36	19	67	36	56	30	42	23	22	12
187	44	119	28	156	37	119	28	78	19	34	8

of the MUTCD minimum pedestrian volume warrant according to the five criteria:

Number	Description	Rating
1	Appropriateness and reasonableness	Poor
2	Complexity	Good
3	Data requirements	Poor
4	Flexibility	Fair/poor
5	Acceptability by traffic engineers	Poor

DEVELOPMENT OF REVISED WARRANT

Based on the review of various warrants in North America and abroad, a number of different concepts were identified, including those that are based on minimum pedestrian volume, delay, weighting of pedestrians with vehicular traffic, and others. It was felt that a warrant based on a minimum volume of pedestrians for a specified period and that conforms to either a minimum delay per pedestrian or a maximum number of adequate gaps per time (1-h, 4-h, etc.) provides the best approach for a revised warrant. With this in mind, development of a revised warrant must take into account the following considerations:

1. Duration of required time,
2. Number of legs for warrant,
3. Minimum pedestrian requirement, and
4. Criteria for gaps or pedestrian delay.

Duration of Required Time

The duration of required time should be somewhere between 1 and 4 h, since less than 1 h is likely to give erroneous results, and collection of pedestrian volume data is simply not practical for most cities for more than 4 h/site. The use of several warrants for several time periods may also allow for more widespread application of the warrant. For example, a signal could be warranted based on either a 1-h warrant, a 2-h warrant, or a 4-h warrant. Locations could warrant a signal based on one high peak hour per day or on lower pedestrian volumes that occur during 4 h (i.e., one morning peak hour, one noon peak hour, and two afternoon peak hours). Based on known distributions of pedestrian volumes by hour, it would be quite simple to develop equivalent pedestrian volume levels for any time duration, as discussed earlier. The requirement of pedestrians per hour would be higher for the 1-h warrant than the 2-h warrant.

Number of Legs for Warrant

The next issue involves the number of intersection legs that should be specified as part of the warrant. Of all the studies reviewed, the MUTCD warrant is the only one that requires that the pedestrian volume be on the highest volume approach, which can cause problems. For example, assume that intersection A has 140 pedestrians/h on each of four approaches during the eighth highest hour of an average day. Location B has 155 pedestrians/h on one approach and 20/h on each of the other two approaches. Location A has a higher traffic volume, but both intersections have traffic volumes greater than 600/h for 8 h. In all, intersection A has 560 pedestrians/h compared with 215/h on intersection B. However, intersection B meets the MUTCD warrant for a traffic signal (with 215 pedestrians/h), but intersection A does not (with 560/h).

This example may be exaggerated to illustrate a point, but this high requirement for volumes on one intersection approach is one of the problems of the current MUTCD minimum pedestrian volume warrant. It is therefore recommended that the warrant should be in terms of pedestrians crossing the highest-volume street (or crossing a midblock location).

Table 4. Summary of existing and recommended minimum pedestrian volumes and data-collection periods.

Source	Minimum Pedestrians per Hour	Time Period	Equivalent Pedestrian Volumes per Day[a]
Box (2)	60	Two at 30 min	420
Canada (6)	60	4 h	710
NCHRP (3)			
King (4)	100	4 h	1190
MUTCD (1)	150	8 h	2272[b]

[a]Based on pedestrian volume distributions from the 1st to the 12th highest hours of pedestrian volume; volumes are rounded to the nearest 10.
[b]At midblock or on one intersection leg.

Minimum Pedestrian Requirement

The minimum required pedestrian volume was the next issue that was addressed. Some of the existing or commonly recommended minimum pedestrian volumes and time periods are given in Table 4. In order to further review the consequences of these various pedestrian warrants, they were applied to a sample of 388 traffic-signalized intersections in Chicago and Washington (where 10 h or more of pedestrian volume data were available). Each location was tested to see how many hours that it would meet each of the pedestrian volume criterion:

1. 60 pedestrians/h (major street),
2. 100 pedestrians/h (major street), and
3. 150 pedestrians/h (highest-volume leg), as per the MUTCD warrant

The results are illustrated in Figure 3, which shows the percentage of the intersections that meet various pedestrian volume criteria for various hours in a day. For example, the MUTCD warrant was met for 1 h or more by about 38 percent of the locations, but was met for 8 h by only about 5 percent of the locations. The warrant of 60 pedestrians/h was met by at least 1 h/day by more than 80 percent

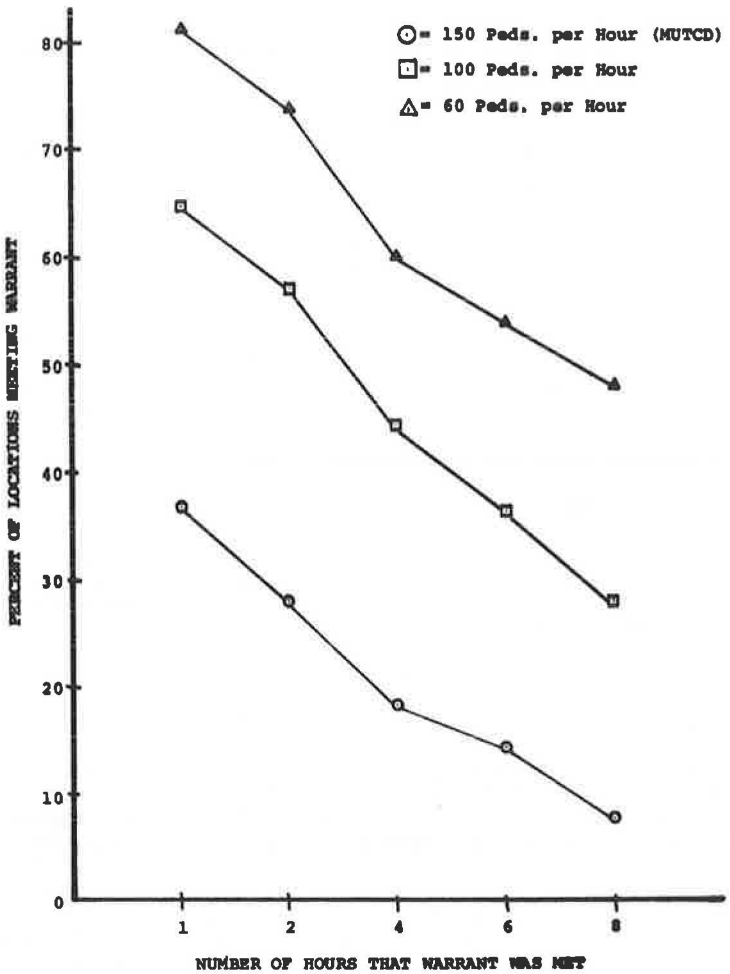

Figure 3. Percentage of locations meeting various pedestrian volume warrants (422 signalized intersections in Chicago and Washington).

of the locations and by at least 4 h for more than 60 percent of the locations. These percentages, of course, are for locations with mostly moderate to high volumes of traffic and pedestrians with existing traffic signals. Therefore, the percentage meeting the warrants would be much lower for a random sample of unsignalized locations.

The purpose of this illustration is to show the relative effect of the length of time and hourly pedestrian volume criteria on the number of traffic signals that would meet various warrants. Note that the percentage of locations meeting any pedestrian volume level decreases drastically as the required time period is increased (high negative slope of the curves). The vertical difference between curves illustrates the effect of different pedestrian hourly volume criteria on the percentage of locations that may satisfy a particular warrant.

To add further insight into an appropriate pedestrian volume criterion, a branching analysis was conducted on 1289 signalized intersections to determine what traffic and roadway variables explain the most variation in pedestrian accident experience. The reader is referred to the work of Zegeer and others (8) for an in-depth analysis of pedestrian accident data. Also, it was hoped that the analysis would provide insights on the traffic and geometric factors that are important in pedestrian accident experience.

The branching program was run by using the Statistical Analysis System (SAS) program package. The program looks for the dichotomous split on the predictor variable (i.e., pedestrian volume, traffic volume, street width, etc.) that best predicts the dependent variable (i.e., pedestrian accidents). The program operates under the principle of least squares and subdivides the data set into mutually exclusive subgroups (9).

The results of the branching analysis showed the following conclusions (8):

1. Pedestrian volume is the variable that by far explains the greatest amount of variation in pedestrian accidents than any other single variable (14.9 percent of variance explained).
2. After trying several groupings of pedestrian volume, the breakpoint occurs for a pedestrian average daily traffic (ADT) level of 1200. In fact, for the 609 locations with pedestrian ADT less than 1200, the mean pedestrian accidents (per location per year) was 0.178 compared with 0.376 for locations with more than 1200 pedestrian ADT.
3. The three variables that were most important in explaining the variation in pedestrian accidents (in order of importance) were pedestrian volume, intersection volume, and intersection operation (one-way and two-way streets).
4. Other variables that were found to be of some importance in explaining pedestrian accidents included bus operation, percentage of vehicle turns, intersection design, area type (CBD, OBD, fringe, or residential), and street approach width.
5. In all, 36.6 percent of the variance in pedestrian accidents was explained by the variables that were included in the analysis.
6. Although all intersections in the analysis

had a traffic signal, the presence or absence of a pedestrian signal indication had no significant effect on pedestrian accident experience.

It should be mentioned that the 1289 intersections in the analysis had traffic signals, so the breakpoint of 1200 pedestrians/day from this analysis may not necessarily be the exact same breakpoint for pedestrian accidents at nonsignalized intersections. If one assumes that the addition of a traffic signal improves pedestrian safety (due to creating artificial gaps in traffic for pedestrians to cross), then the critical breakpoint for unsignalized intersections would logically be something less than 1200 pedestrians/day. Thus, a value of 1200 would be a conservatively high value. Many might argue, however, that in areas of poor signal compliance, the addition of a traffic signal could actually reduce pedestrian safety due to the high incidence of pedestrian and motorist signal violations. Obviously, it would be very difficult to define the optimal pedestrian breakpoint value for all roadway situations, but 1200 pedestrians/day may be a reasonable approximation based on available data.

An intersection pedestrian ADT of 1200 at four-legged intersections corresponds to a pedestrian volume of 750 crossing the major street (two highest volume legs) based on 62.5 percent (36 + 26.5 percent) of pedestrians crossing the highest volume legs. Based on hourly pedestrian distributions, this would convert to the following volumes for the first, second, and fourth highest hourly volume:

Volume Period	Equivalent Pedestrian ADT (nearest 10 pedestrians)
ADT	750
1st highest hour	110
2nd highest hour	90
4th highest hour	60

The corresponding minimum pedestrian volume for the fourth highest hour corresponds to the Canadian pedestrian volume criterion of 60 pedestrians/h for 4 h. It would be stricter than the Box warrant, which requires 60 pedestrians/h for each of two 30-min periods (2). The pedestrian volume criterion would be less strict than the 100 pedestrians/h for 4 h as required by King (4) and NCHRP (3). For shorter time periods of 2 or 1 h, pedestrian volumes of 90 and 110/h would be required, respectively.

Criteria for Gaps or Pedestrian Delay

A pedestrian signal warrant must consider not only pedestrian volumes but also the time available for pedestrians to cross the street (i.e., available gaps in traffic). The number of adequate gaps in traffic is directly related to various combinations of traffic speed, traffic volume, and traffic arrival distribution. Further, the number and duration of gaps needed for safe pedestrian crossings is a function of street width, pedestrian walking speed, and pedestrian volume (and/or pedestrian group size). The number of adequate gaps in traffic can be quickly and easily determined based on field surveys (or other methods), as described by the Institute of Transportation Engineers (ITE) (10).

A gap-based warrant of less than 60 acceptable gaps/h is currently the school crossing warrant prescribed in MUTCD. This gap-based criterion actually accounts for site-specific combinations of street width, pedestrian walking speed, vehicle speed, traffic volume, and traffic arrival distribution. It is therefore conceptually appealing as well as practical to use along with a pedestrian volume criterion for a limited time period per site.

In the absence of additional objective information, the minimum pedestrian volume criterion was selected as follows. The minimum required pedestrian volume crossing the major street per hour for an average day must be (a) 60 or more for each of any 4 h, or (b) 90 or more for each of any 2 h, or (c) 110 or more during the peak hour.

In addition to a minimum pedestrian volume of those stated above, the number of adequate gaps in the traffic stream (during the same periods as above) should be less than 60/h during the same period when the pedestrian volume criterion is satisfied.

CONCLUSIONS AND RECOMMENDATIONS

The purpose of this paper was to evaluate existing MUTCD warrants related to pedestrian signals and actuation devices by examining the existing literature and operational practice. If the existing MUTCD warrants were found to be inadequate, new warrants were to be developed.

The MUTCD minimum pedestrian volume warrant was found to be unacceptable in terms of its (a) appropriateness to real-world conditions, (b) data requirements, (c) flexibility, and (d) acceptability to practicing traffic engineers.

Based on all available literature and on existing pedestrian signal warrants, a number of different warrant concepts were examined. The preferable concept was found to be one that incorporates a minimum pedestrian volume per hour and a number of adequate gaps per hour. Based on an in-depth study of hourly pedestrian volume distributions and an analysis of data at 1297 intersections, the following minimum pedestrian volume warrant was recommended.

A traffic signal is warranted if

1. The minimum pedestrian volume crossing the major street equals or exceeds (a) 60/h for each of any 4 h, or (b) 90/h for each of any 2 h, or (c) 110/h during the peak hour;
2. The number of adequate gaps in the traffic stream on the major street is less than 60/h during the same period when the pedestrian volume criterion is satisfied; and
3. When a traffic signal is warranted based on criteria 1 and 2 above, pedestrian indications should be used; the warrant is for either midblock locations or for intersections.

The recommended minimum pedestrian volume warrant has some similarities to warrants recommended by Box (2) and the Canadian warrant (6).

ACKNOWLEDGMENT

The opinions and viewpoints expressed in this paper are ours and do not necessarily reflect the viewpoints, programs, or policies of the U.S. Department of Transportation or any state or local agency.

Discussion

K. Todd

When signal warrants first came into being half a century ago, their purpose was twofold: (a) to give traffic engineers satisfactory guidelines that justified the decision to install or not to install a signal on the basis of operational and safety considerations, and (b) to convince the public and elected officials of the reasonableness of such a decision.

Installation of pedestrian and other signals is often preceded by requests from the public and by hearings and discussions at public meetings. Statistical analyses and mathematical computations do not easily convince pedestrians who are asking for the protection of a signal, nor do they convince motorists who fear additional delays. In consequence, a further criterion--acceptability by the public--might be added to the five criteria listed by Zegeer, Khasnabis, and Fegan.

From the public's point of view, the proposed warrant may be queried on the following issues:

1. A pedestrian signal is warranted where the minimum pedestrian volume crossing the major street equals or exceeds 110 during the peak hour. The stipulation gives rise to the following question. If fewer than 110 pedestrians (100 of them, for example) are expected to cross the major street safely and without undue delay during the peak hour without the help of a signal, why would a signal ever be warranted in circumstances when pedestrian volumes are even lower?
2. If pedestrians are refused a signal unless the number of adequate gaps in traffic on the major street is less than 60/h, why do they have to wait at a signal during periods of the day when the number of such gaps is larger?
3. The pedestrian signal is warranted on the assumption that there are fewer than 60 adequate gaps/h in traffic on the major road and that the vehicle volume on the minor road is too low to warrant a signal. If 60 pedestrians/h, which represent 36 percent of the total pedestrian volume, justify the installation of a signal to help them across the highest-volume leg of the major road, the two low-volume legs on the minor road would likely be crossed by 36 (21.4 percent) and 27 (16.1 percent) pedestrians, respectively, during the same hour. The question may be asked why pedestrians wishing to cross these low-volume legs have to be controlled by a signal, seeing that neither the vehicle volumes on the minor road legs nor the pedestrian volumes warrant it.

These issues are somewhat wider than those addressed by the authors and may perhaps be dealt with more appropriately by the traffic engineering profession as a whole. So long as these questions remain unanswered, the warrant will suffer from a credibility problem.

Authors' Closure

We appreciate Todd's comments and his interest in our paper. The fact that his comments are from the "public's point of view" is refreshing, and we will attempt to address each of the questions raised.

First of all, Todd suggests that acceptability by the public might be added as a criterion in selecting an appropriate pedestrain signal warrant. Although we agree that citizen input is often useful in many transportation-related areas, the average citizen does not have an adequate understanding of how traffic signals affect the safety and operations of pedestrians and vehicles. In terms of public preferences, we have found that pedestrians are likely to favor the installation of traffic signals to aid their crossings, while motorists would prefer not to be stopped at a traffic signal due to pedestrians, particularly since pedestrians are unjustly treated as second-class citizens by many motorists.

Todd's next question involves the minimum pedestrian volume criterion of 110 pedestrians/h on the major street. We believe that some minimum pedestrian volume level is needed as part of the warrant, and our analyses indicated that 1200 pedestrians/day was an appropriate level. This daily volume translates into 110 pedestrians/h during the peak hour based on 24-h distributions of pedestrian volume. When Todd asks why a signal could be warranted for lower volumes, we assume he is referring to our 2-h volume criterion (90 or more pedestrians/h) and our 4-h criterion (60 or more pedestrians/h). It should be understood that all three criteria correspond to approximately the same daily (24-h) pedestrian crossings. Therefore, public agencies can use our warrant with as little as 1 h of data or as much as 4 h of data.

The next two issues pertain to the number of adequate gaps. Because traffic and pedestrian volumes commonly fluctuate greatly throughout the day, the development of any type of signal warrant must consider some specified time period due to practical considerations in applying the warrant. Thus, traffic signal warrants involve criteria for some critical or high-volume period when safety and operational problems are most prevalent (i.e., peak 8 h of an average day). For signalized intersections with low nighttime traffic, a flashing amber (caution) signal may be used on the main street with a flashing red (stop and proceed when clear) signal on the side street.

Regarding the need to stop pedestrians and traffic on the side street (in Todd's third major point), the installation of a traffic signal on the main street implies that traffic will be given a green interval for probably most of the cycle. Thus, stop control (i.e., a red light) is needed for side street vehicles to prevent large numbers of right-angle collisions with main street through vehicles. Also, pedestrian street crossings should be guided by the signal control (preferably WALK/DON'T WALK signals, if present) for obvious safety reasons.

With regard to warrant credibility, we have found that the current MUTCD minimum pedestrian volume warrant suffers from a severe credibility problem. At a recent TRB conference session, one city traffic engineer stated that the existing minimum pedestrian volume warrant is so unrealistically high that it casts a shadow of doubt on the other signal warrants, even though most of the other warrants seem to be reasonable for most real-world conditions. This comment was typical of comments we have received from traffic engineers throughout the country.

Based on our research efforts, we believe our proposed warrant to be superior to the current warrant. The similarities of our warrant to the Canadian warrant (60 pedestrians/h for 4 h), although coincidental, are encouraging. Also, the concept of a minimum pedestrian volume criterion and consideration of the number of acceptable gaps is shared by other researchers. Perhaps further research could be useful to determine the number of new traffic signal installations (and corresponding costs) that would result from the adoption of our warrant. The effect of such new signal installations on safety and operations under various conditions should also be determined for signals installed based on a revised warrant.

One other important point to consider is that the current warrant is so unrealistically high that little possibility exists in many cities for warranting a traffic signal based on pedestrian considerations, as discussed in our paper. This indicates that the needs of pedestrians may be unjustly ignored, and that pedestrians are too often considered merely as a hindrance to traffic flow in our society. We hope that the results of our study, as well as other related studies, will be helpful in the modification of the minimum pedestrian volume warrant.

REFERENCES

1. Manual of Uniform Traffic Control Devices. FHWA, U.S. Department of Transportation, 1978.
2. P.C. Box and Associates. Assembly, Analysis, and Application of Data Warrants for Traffic Control Signals. National Joint Committee on Uniform Traffic Control Devices, March 1967.
3. E.B. Lieberman and others; KLD Associates. Traffic Signal Warrants. NCHRP, Project 3-20, Final Rept., Dec. 1976.
4. G.F. King. Pedestrian Delay and Pedestrian Signal Warrants. TRB, Transportation Research Record 629, 1977, pp. 7-13.
5. J.C. Tanner. The Delay to Pedestrian Crossing a Road. Biometrika, Vol. 38, 1951, pp. 382-383.
6. Installation Warrants for Traffic Control Signals. Canadian Good Roads Association, Ottowa, Ontario, Canada, Part B, Division 2, May 1966.
7. R. Cameron. Pedestrian Volume Characteristics. Traffic Engineering Magazine, Jan. 1977, pp. 36-37.
8. C.V. Zegeer, K.O. Opiela, and M.J. Cynecki. Effect of Pedestrian Signals and Signal Timing on Pedestrian Accidents. TRB, Transportation Research Record 847, 1982, pp. 62-72.
9. Statistical Analysis System, SAS Application Guide. SAS Institute, Cary, NC, 1980.
10. A Program for School Crossing Protection. ITE, Washington, DC, 1971.

Publication of this paper sponsored by Committee on Pedestrians.

Measurements and Analysis of Degradation of Freight Car Reflectors in Revenue Service

JAMES L. POAGE AND JOHN B. HOPKINS

Accidents at railroad-highway crossings in which a motor vehicle ran into the side of a train during dawn, dusk, and darkness accounted for 13.6 percent of all fatalities and 21 percent of all injuries in crossing accidents during 1980. A possible remedial action for this problem is to mount retroreflective material on the sides of freight cars that, when illuminated by vehicle headlights, may give an indication of the presence of a train in the crossing. Results of measurements conducted on freight-car-mounted reflectors to provide data on the durability of reflectors in revenue service are presented. Reflective intensity measurements were made on engineer-grade retroreflective sheeting on Canadian freight cars; this material has been installed on the side sills of Canadian freight cars since 1959. Reflective intensity measurements were also made over a six-month period on high-intensity reflective sheeting on 19 Boston and Maine Railroad freight cars. The Canadian reflector measurements on engineer-grade reflectors indicated rapid deterioration in the reflective intensity. Data from tests on the Boston and Maine Railroad strongly indicate that high-intensity reflectors deteriorate in the railroad environment at a similar rate, although the limited time for the high-intensity tests precludes absolute conclusions on high-intensity reflector durability. The rapid rate of degradation in reflective intensity has implications for the size of reflectors that might be mounted on freight cars, the useful life of the reflectors, the importance and scheduling of washing of the reflectors, and the cost and cost-effectiveness of reflectorization. Equations that describe the trade-off between reflector size and washing interval are developed.

Accidents at railroad-highway crossings in which a motor vehicle ran into the side of a train during dawn, dusk, and darkness accounted for 13.6 percent of all fatalities and 21 percent of all injuries in crossing accidents during 1980. A possible remedial action for this problem is to mount retroreflective material on the sides of freight cars that, when illuminated by vehicle headlights, may give an indication of the presence of a train in the crossing. Previous research (1) has addressed the issues of potential benefits and required reflector brightness. However, a major remaining uncertainty concerning this safety measure is the rate at which dirt and age affect the reflectors. This paper presents the results of measurements performed on freight-car-mounted reflectors to provide information on the durability of reflectors on cars in revenue service. The rate of degradation in reflective intensity has implications for the size of reflectors that might be mounted on freight cars, for the useful life of the reflectors, for whether washing of the reflectors would be necessary, and thus for the cost-effectiveness and practicality of reflectorization. This paper also investigates the relation between reflector size and frequency of washing.

OVERVIEW OF REFLECTIVE INTENSITY MEASUREMENTS

Several types of tests of freight car reflector durability are described in this paper. In one test, the reflective intensity of reflectors on 208 Canadian freight cars was measured. Since May 1959, the Canadian Transport Commission (CTC) has required that reflective markings be installed on the side sills of Canadian freight cars. Observations of the visibility of reflectors on Canadian trains at night were also made at three railroad-highway crossings. The tests on Canadian freight cars were conducted jointly by the Transportation Systems Center (TSC) and CTC. The reflectors measured on Canadian freight cars are engineer-grade retroreflective sheeting. In another test, high-intensity retroreflective sheeting was placed on 33 Boston and Maine Railroad (B&M) freight cars during spring and summer 1981. Reflective intensity measurements on 19 of these cars were made during a six-month period.

The reflective intensity measurement tests on Canadian freight cars suggest a rapid decline in reflector reflective intensity to an average of 23 percent of initial value after six months, to 14 percent after one year, and to 5 percent after two