A MULTI-CRITERIA-BASED GUIDELINE FOR MARKED AND UNMARKED PEDESTRIAN CROSSWALKS AT UNSIGNALIZED INTERSECTIONS

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Submitted for ITE Western District Student Paper Award
Date Submitted: April 1st, 2013

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ABSTRACT

There have been controversial perceptions with respect to the use of marked pedestrian crosswalks at unsignalized intersections over the years. Several agencies tend to prefer marked crosswalks at most locations with the expectation of improving pedestrian mobility and safety. However, several studies conclude that marked crosswalks actually involve higher pedestrian accident rates than unmarked crosswalks. Such controversial claims make it difficult for state and local agencies to develop policies pertaining to pedestrian crosswalks. Existing guidelines for determining marked and unmarked crosswalk types are normally presented as descriptive statements or mostly relying on a single dominate factor like pedestrian volume. One of the major issues lies in the lack of comprehensive consideration and interpretation of all potential variables. A new guideline is presented to help select marked and unmarked crosswalks at unsignalized intersections with no traffic signals or stop signs on the major street approach. The guideline is based on a combination of revised multi-criteria decision analysis methodologies, PROMETHEE and the Analytical Hierarchy Process. A ranking score considering potential factors, including variables such as volume, speed limit, and pedestrian related crash records is produced to represent the likelihood of using a marked or unmarked crosswalk. The proposed guideline was further applied to a case study involving 32 unsignalized intersections in Nevada and the study showed promising results with the guideline.

Key Words: Pedestrian Crosswalks; Marked and Unmarked; Unsignalized Intersections; Multi-criteria Decision Analysis; PROMETHEE and Analytical Hierarchy Process Methodologies.

INTRODUCTION

Crosswalks at unsignalized intersections have become the subject of numerous studies over the past 30 years. One of the critical aspects is whether a marked crosswalk should be provided on major streets. The original intention of marking crosswalks was to guide pedestrians and also reduce the potential conflicts of vehicles and pedestrians. However, there have been controversial perceptions and study results concerning the performance of marked and unmarked crosswalks that challenge this elementary purpose (*1*, *2*, *3*, *4*). Former study results show that marked crosswalks always reveal poor safety performances compared with unmarked ones, especially at unsignalized intersections and midblock crossing locations. Although there were differences among locations, data collection techniques, and statistical analysis methodologies in these studies, they conclude that marked crosswalks consistently involve higher pedestrian accident rates. Consequently, states and local agencies are in a dilemma on determining the installation of marked and unmarked crosswalks. Over the years, studies conducted in the United

States and overseas have advanced several guidelines helping the government decide under what conditions a marked crosswalk would be a better choice. Some of these guidelines have similarities in ordinary parts, yet others may be particular to their own traffic and safety situations.

Currently, the widely used national guidance regarding crosswalk marking is documented in the Manual on Uniform Traffic Control Devices (MUTCD) Section 3B-17 and 3B-18 (*5*). It states that crosswalks should be marked at all intersections where there is substantial conflict between vehicular and pedestrian movements. Marked crosswalks also should be provided at other appropriate points of pedestrian concentrations, such as at loading islands and midblock pedestrian crossings. This guideline suggests considering pedestrian and traffic volumes and intersection geometries while deciding to mark the crosswalks or not. However, it lacks further quantitative criteria regarding these factors. The limited descriptive statements in the MUTCD are not adequate for field application.

A complement of foregoing general guidelines was put forward by Zegeer et al. in 2005 for the Federal Highway Administration (FHWA). This study was based on five years of pedestrian-related crash data in 1,000 marked crosswalks and 1,000 unmarked crosswalks used as comparison sites in 30 United States cities. They divided crosswalks into three possible ratings: (1) candidate sites for marked crosswalks (i.e., marked crosswalks must be installed carefully and selectively); (2) probable increase in pedestrian crash risk may occur if crosswalks are added without other pedestrian facility enhancements; and (3) marked crosswalks alone are insufficient, since pedestrian crash risk may be increased by providing marked crosswalks (*6*). Basically, this federal guidance comprehensively considers combinations of four variables, i.e., speed limit, vehicle ADT, number of travel lanes, and median type. This guideline indeed points out that determining a pedestrian crosswalk type belongs in the multi-criteria analysis territory. Even though pedestrian-related crash record is mentioned within, the actual application of the guideline ignored this factor.

Later, Fitzpatrick et al. expanded the scope beyond just examining marked versus unmarked crosswalks and evaluated the effectiveness of many other pedestrian safety countermeasures for uncontrolled crossings, including red signal and beacon devices, enhanced, high-visibility signs, etcetera (*7*). These countermeasures are there to enhance pedestrian safety, and therefore, combinations of several traffic control devices or design elements were recommended to control needs of both pedestrians and motorists (*7*, *8*). This guideline is in a flowchart format involving key variables such as speed limit and volumes, and the final recommendation, not necessarily for selecting marked crosswalks, is based on the total pedestrian delay along with the expected compliance.

The Arizona Department of Transportation and some other local agencies such as the City of Reno in Nevada are using a similar guidance named “Point System” which also considers speed limit and vehicle ADT variables. This guideline prefers marked crosswalks at locations with higher pedestrian and vehicular traffic volumes. The issue is that when traffic volume is high enough it would be difficult for pedestrians to seek an acceptable gap to cross. In that case, pedestrians should not be encouraged to cross at that location considering the safety issues. The reason why these guidelines provide such preference is that no balance or connection between variables has been taken into consideration. Certain factors, like volume, will dominate the final decision.

In short, deciding a pedestrian crosswalk type is quite complex; especially when there is no clear-cut evidence to conclude that either marked or unmarked crosswalks are adequate. States and agencies prefer to conduct engineering studies to decide whether a marking is needed. These current studies are blind to some extent because of two reasons. On the one hand, there are many flaws with the data regarding pedestrian crashes, such as incompleteness, inaccuracy, and inconsistency. Consequently crash-based safety analysis will be hampered by several shortcomings, such as randomness and rarity of crash occurrences, lack of timeliness, and inconsistency in crash reporting (*9*). On the other hand, the existing guidelines are either qualitative statements or mostly rely on a single dominate factor like pedestrian volume. For example, Clark County, in Nevada, uses 20 pedestrians per hour as the determination to install a marked crosswalk; however, they do not believe this guideline is sufficient. Such guidelines lack a balanced consideration of all potential factors, such as intersection geometry, vehicle speed, etc.; therefore, the decision process is biased at some locations. Another issue is how to evaluate the impact of each factor in the decision process synthetically. It can be seen that determining pedestrian crosswalk types is a systematic process involving intricate decision rules, especially when both mobility and safety factors are cogitated altogether. Since these potential impact factors have different categories and criteria, the crosswalk type decision making process can be considered as a typical multi-criteria analysis problem. Accordingly, one can comprehend the perplexed nature of the crosswalk issue. It is important to properly guide the installation of crosswalks and explicitly evaluate each criterion since pedestrians are deeply affected from the consequences. It is the aim of this study to complement the blindness and come up with a more applicable guidance for the installation of marked crosswalks.

MULTI-CRITERIA METHODOLOGY

A multi-criteria decision problem can be described as a decision making problem with m criteria and n alternatives, and let $C_1, C_2 \cdots C_m$ and $A_1, A_2 \cdots A_n$ denote the criteria and alternatives, respectively. A standard feature of a multi-criteria decision making methodology is the decision matrix as shown in Equation (1). In the matrix, each row belongs to a criterion and each column describes the performance of an alternative. The score x_{ij} describes the performance of alternative A_j against criterion C_i.

$$D = X_{ij} = \begin{matrix} & & x_1 & x_2 & \cdots & x_n \\ & & A_1 & A_2 & \cdots & A_n \\ w_1 & C_1 \\ w_2 & C_2 \\ \vdots & \vdots \\ \vdots & \vdots \\ w_m & C_m \end{matrix} \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \cdots & \cdots & \vdots \\ \vdots & \cdots & \cdots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \tag{1}$$

In the decision matrix, the weights $\{w_1, w_2, \cdots w_m\}$ are assigned to the criteria. Weight w_i reflects the relative importance of criteria C_i to the decision. The weight can be obtained separately using the Analytic Hierarchy Process (AHP) (*10*) approach. Equation (2) then computes the overall performance of each alternative.

$$F(A_j) = \sum_{i=1}^{m} w_i \, r_{ij} \tag{2}$$

Where r_{ij} is the normalized performance rating of alternative A_j against criterion C_i.

A wide range of multi-criteria decision analysis methodologies, such as the AHP approach, Simple Additive Weighting Method (*11*), TOPSIS Method (*12*), Out-Ranking Method, etc. can achieve a final ranking or scoring for the decision alternatives. Considering maneuverability and practical applicability, this study uses the PROMETHEE methodology as a foundation to develop the guideline. PROMETHEE methodology is a member of the out-ranking method's family which solves complex choice problems with multiple criteria and multiple participants (*13*). This method is well-known for its indication of the degree of dominance of one alternative over another and has been widely used, for example, in choosing a solid waste management system (*14*), for locating a waste treatment facility (*15*), and other Environmental Impact Analysis (EIA) projects. Nevertheless, the concept in the PROMETHEE method does not possess a wide application in the transportation field. This study attempts to exploit an approach that assists decision making with the advantages of this method.

The PROMETHEE preference structure is based on pair-wise comparisons similar to the AHP approach. The deviance between the evaluations of alternatives on a particular criterion is considered. For small deviations, the decision-maker will allocate a small preference to the best alternative and even possibly no preference if it is considered that this deviation is negligible (*16*). The out-ranking degree $\prod(a_{k,} a_l)$ in Equation (3) describes the credibility of the out-ranking relation that alternative a_k is better than alternative a_l.

$$\prod(a_{k,}a_l) = \sum_{j=1}^{n} w_j F_j\,(a_{k,}a_l) \quad (3)$$

Where, $F_j(a_{k,}a_l)$ is the preference function; and w_j is the relative importance of the different criteria.

In contrast to using normalized subjective rating scores from Equation (2), the PROMETHEE method uses a pre-defined preference function to perform a pair-wise comparison of the global performance of alternatives under each criterion. The preference function $F_j(a_{k,}a_l)$ is the core of this method. This study establishes a new preference function embedded in the PROMETHEE method to develop the guideline.

GUIDELINE DEVELOPMENT

Based on the basic guidelines documented in the MUTCD and FHWA, marked crosswalks can be selected as a candidate at locations where, (i) there is substantial conflict between vehicular and pedestrian movements; (ii) there is a need to guide pedestrians considering the geometry layout of the intersection; and (iii) the vehicular speed limit is less than 40 mph and the vehicle ADT is less than 12,000. Given a specific unsignalized intersection, the above guidance will help judge whether the location can be seen as a candidate location for crosswalk markings. If not, unmarked crosswalks would be the clear choice. For candidate locations, additional analysis should be provided. In accordance with discussions above, determining a pedestrian crosswalk type is a typical multi-criteria decision problem involving alternatives Mark and Unmark crosswalk types as well as several multi-criteria decisive variables. Based on this idea, a new guideline is developed following the four consecutive processes below.

Step 1: Identify Variables and Generate Sub-Decision Matrices

The variables were obtained from previous literature and a comprehensive statewide agency survey involving the City of Las Vegas, City of North Las Vegas, City of Henderson, Clark County, City of Reno, and Carson City, Nevada. Typical questions were asked about the variables, criteria, and their degree of importance that should be considered in developing guidelines for marked crosswalks at unsignalized intersections. Engineers in Nevada agree that the policy preference tendency regarding pedestrian crosswalks may be different for different jurisdictions and should be considered together with other variables. Ten major variables are identified in Table 1.

Two variables, C5 Available Gaps and C6 Distance to Nearby Crosswalk, which rarely grasp attention, are put forward in this study. The available gaps of major-street vehicles are closely related to the traffic volumes and headways. In real-world conditions, when drivers fail to yield to pedestrians, pedestrians have to seek a gap in order to cross. Therefore, if the available gaps are small, it is a risk to guide pedestrians to cross. The number of available gaps is defined here as the average number of unimpeded vehicle time gaps equal to or exceeding the required pedestrian crossing time in an average 5-minute period during the peak vehicle hour. Consequently, a site with a higher number of available gaps makes pedestrians choose a gap and pass with ease. In this case, the marked crosswalk would have a higher preference than the unmarked crosswalk. Another concern lies in the distance to a nearby crosswalk. If the subject intersection is within a short distance of the nearby crosswalk, it is less likely to mark the crosswalk. This encourages pedestrians to cross the already marked crosswalk. This type of unsignalized intersection is pretty common in the U.S. Therefore, when the distance between the study site and its nearby crosswalk is within a relatively short threshold, namely 200 feet, a marked crosswalk is not preferred.

TABLE 1 Explanatory Variables of Guideline

Variables		Abbreviation	Evaluation
C1	Policy Preference Tendency	PPT	0-N/A; 1-Conservative; 2-Moderate; 3-Aggressive
C2	Current Crosswalk Condition	MOU	0-Unmarked Crosswalk; 1-Marked Crosswalk
C3	Geometry Layout of Intersection	GL	3-Legs; 4-Legs
C4	Number of Travel Lanes	NTL	1-Lane; 2-Lanes; 3-Lanes and so forth
C5	Available Gaps	AG	Average number of gaps per 5-minute period
C6	Distance to Nearby Crosswalk	DNC	Unit: feet (ft)
C7	Vehicle Speed Limit	SL	Unit: miles per hour (mph)
C8	Traffic Volumes	TV	Unit: vehicles per hour (vph)
C9	Pedestrian Volumes	PV	Unit: pedestrians per hour (peds/hour)
C10	Pedestrian Accident Occurrence	PRC	Unit: accidents in 3- to 5-year period (acc./3-5 yrs)

Note: C1-C10 are the symbols given to each variable for programming; Abbreviations are defined by this study; N/A-Not Applicable.

Additionally, ten variables and their scores g_{ij} to different criteria under mark versus unmark circumstances are generated and the decision matrix is then formed. Each variable is scored a value between 0 and 10. For the sake of simplicity, an assumption is made that a higher score value means better preference for the alternatives. In practice, a score of 10 suggests that a certain type of crosswalk is absolutely needed. For example, four categories are given to variable C1 Policy Preference Tendency: 0-N/A (Not Applicable), 1-Conservative, 2-Moderate, and 3-Aggressive. An initial recommendation independent from agency preference will be implemented when zero is input for variable C1. The conservative preference means a marking is a preferred choice since it satisfies the ground needs to guide pedestrians. Therefore, a score of 10 is assigned for the conservative preference to the alternative Mark. On the contrary, the aggressive tendency indicates that unmark is a preferred choice because it is believed that marking is not necessary at a specific site. Consequently, a score 10 is assigned from aggressive judgment to alternative Unmark.

Step 2: Determine Weights for Variables

The relative importance of each variable is identified after establishing the decision matrices. The importance is represented by the assigned weight for each variable. This study applies the AHP pair-wise comparison approach to obtain weights w_i. The evaluation of each pair is based on the results from the statewide agency survey. Considering the discussions in the MUTCD and FHWA pertaining to speed limit, volume and safety factor, the weights for all variables are designed to be dynamic and will fluctuate according to six conditions demonstrated in Table 2. Firstly, the guideline will present an initial recommendation independent of the policy preference factor. Additionally, if the speed limit and volume exceed the pre-defined thresholds they are considered critical factors for the decision making of crosswalk types. Besides, if the site with severe crash record does not have a marked crosswalk, a decision is inclined to install a marked crosswalk in order to provide a guided path for pedestrians; if the site with sever crash record already has marked crosswalks, an engineering judgment will be preferred to further discuss the possibility of installing other effective countermeasures.

TABLE 2 Dynamic Variable Weights

Condition	w_{PPT}	w_{MOU}	w_{GL}	w_{NTL}	w_{AG}	w_{DNC}	w_{SL}	w_{TV}	w_{PV}	w_{PRC}
$PPT = 0$	N/A	0.0263	0.0304	0.0477	0.1339	0.1069	0.2112	0.0536	0.1982	0.1918
$SL \geq 40mph$ & $TV \geq 1{,}200vph$	0.0150	0.0150	0.0150	0.0150	0.0150	0.0150	0.4500	0.3600	0.0536	0.0464
$SL \geq 40mph$ & $PV \geq 20$ peds/hr	0.0167	0.0166	0.0166	0.0167	0.0301	0.0167	0.4500	0.0167	0.3600	0.0599
$PRC \geq 4$ acc./yr & $MOU = 0$	0.0011	0.1885	0.0002	0.0110	0.0061	0.0021	0.0875	0.0120	0.1685	0.5230
$PRC \geq 4$ acc./yr & $MOU = 1$	0.4666	0.0425	0.0425	0.0425	0.0425	0.0425	0.0875	0.0875	0.0688	0.0771
Otherwise/General Case	0.0559	0.0263	0.0304	0.0337	0.1339	0.0969	0.2072	0.0436	0.1892	0.1829

Note: N/A-Not Applicable.

Step 3: Determine Preference Function and Preference Degrees

In order to take the deviations and the scales of the criteria into account, a preference function is associated to each criterion. This study defines the preference function as $P(M, U)$ to represent the degree of the preference of alternative Mark over Unmark for criterion C_i. A linear threshold function is utilized and defined by Equations (4)-(6). When the judging difference between two alternatives is relatively small, e.g. less than a predetermined threshold, there is no difference existing in the preference process. Equally, if the judging difference passes a predetermined strict threshold, the preference is absolute. Otherwise, the preference will follow a linear function with a slope of $1/(p - q)$ in which parameters p and q are obtained by testing various combinations of values. For this study, considering the preference degree is following a normalized form, the meaning of the preference value is explicitly explained in Table 3. The preference scores for each variable and the corresponding preference degrees are presented in Table 4.

$$P(M, U) = F\{d_i(M, U)\}, 0 \leq P(M, U) \leq 1, i = 1, 2, \cdots n \quad (4)$$

$$d_i(M, U) = g_i(M) - g_i(U), i = 1, 2, \cdots n \quad (5)$$

$$F(d) = \begin{cases} 0 & d \le q \\ \frac{d-q}{p-q} & q < d \le p \\ 1 & d > p \end{cases} \tag{6}$$

TABLE 3 Meaning of Preference Function

Preference Function	Meaning	Preference Function	Meaning
$P_i(M,U) = 0$	no preference	$P_i(U,M) = 0$	no preference
$P_i(M,U) \approx 0$	weak preference for marking	$P_i(U,M) \approx 0$	weak preference for unmarking
$P_i(M,U) \approx 1$	strong preference of marking	$P_i(U,M) \approx 1$	strong preference of unmarking
$P_i(M,U) = 1$	strict preference of marking	$P_i(U,M) = 1$	strict preference of unmarking

Note: M-Mark; U-Unmark.

TABLE 4 Criteria & Scores of Variables and Corresponding Preference Degrees

C1	**PPT**	**0**	**1**	**2**	**3**	**C2**	**MOU**	**0**	**1**		
Scores g_{1j}	M	N/A	10.00	5.00	0.00	Scores g_{2j}	M	7.30	2.70		
	U	N/A	0.00	5.00	10.00		U	2.70	7.30		
Degrees	$P_1(M,U)$	N/A	1.00	0.00	0.00	Degrees	$P_2(M,U)$	0.53	0.00		
	$P_1(U,M)$	N/A	0.00	0.00	1.00		$P_2(U,M)$	0.00	0.53		
C3	**GL**	**4L**	**3L**	**C4**	**NTL**	**>5**	**4**	**3**	**2**	**1**	
Scores g_{3j}	M	6.42	7.42	Scores g_{4j}	M	8.56	7.63	7.12	2.88	2.50	
	U	3.58	2.58		U	1.44	2.73	2.88	7.12	7.50	
Degrees	$P_3(M,U)$	0.65	0.61	Degrees	$P_4(M,U)$	1.00	0.75	0.41	0.00	0.00	
	$P_3(U,M)$	0.46	0.00		$P_4(U,M)$	0.00	0.12	0.00	0.41	0.67	
C5	**AG**	**>10**	**6-10**	**4-6**	**<4**	**C6**	**DNC**	**501-750**	**251-500**	**201-250**	**≤200**
Scores g_{5j}	M	9.25	7.65	5.00	2.30	Scores g_{6j}	M	7.25	5.00	2.75	1.00
	U	0.75	2.35	5.00	7.70		U	2.75	5.00	7.25	9.00
Degrees	$P_5(M,U)$	1.00	0.76	0.55	0.00	Degrees	$P_6(M,U)$	0.50	0.00	0.00	0.00
	$P_5(U,M)$	0.00	0.00	0.45	0.80		$P_6(U,M)$	0.00	0.35	0.75	1.00
C7	**SL**	**55**	**45**	**35**	**25**	**15**					
Scores g_{7j}	M	0.00	0.00	8.64	7.99	8.50					
	U	10.00	10.00	5.00	2.01	1.50					
Degrees	$P_7(M,U)$	0.00	0.05	0.96	0.89	1.00					
	$P_7(U,M)$	1.00	1.00	0.26	0.00	0.00					
C8	**TV**	**>600**	**501-600**	**401-500**	**301-400**	**201-300**	**101-200**	**≤100**			
Scores g_{8j}	M	9.00	8.00	7.50	7.25	7.00	6.75	2.50			
	U	1.00	2.00	2.50	2.75	3.00	3.25	7.50			
Degrees	$P_8(M,U)$	1.00	1.00	0.67	0.50	0.33	0.17	0.00			
	$P_8(U,M)$	0.00	0.06	0.17	0.22	0.36	0.50	0.67			
C9	**PV**	**>40**	**31-40**	**26-30**	**21-25**	**16-20**	**11-15**	**6-10**	**≤5**		
Scores g_{9j}	M	9.25	8.85	8.50	7.58	7.25	3.00	2.75	1.50		
	U	0.75	1.15	1.50	2.42	2.75	7.00	7.25	8.50		
Degrees	$P_9(M,U)$	1.00	1.00	1.00	0.72	0.50	0.33	0.17	0.00		
	$P_9(U,M)$	0.00	0.05	0.15	0.20	0.26	0.33	0.00	1.00		
C10	**PRC**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**0**	
Scores g_{10j}	M	9.50	9.50	8.50	8.00	7.75	7.30	6.75	5.00	2.75	
	U	0.50	0.50	1.50	2.00	2.25	2.70	3.25	5.00	7.25	
Degrees	$P_3(M,U)$	1.00	1.00	1.00	1.00	0.83	0.53	0.17	0.00	0.00	
	$P_3(U,M)$	0.00	0.04	0.08	0.16	0.28	0.32	0.32	0.46	0.50	

Note: M-Mark; U-Unmark; N/A-Not Applicable.

Step 4: Determine Complete Ranking Scores of Each Alternative

Afterwards, weighted multi-criteria preference index $\pi(\mathrm{M,U})$ for Mark over Unmark and $\pi(\mathrm{U,M})$ for Unmark over Mark are defined considering all the criteria:

$$\pi(\mathrm{M,U}) = \sum_{i=1}^{10} w_i P_i(\mathrm{M,U})\,;\, \pi(\mathrm{U,M}) = \sum_{i=1}^{10} w_i P_i(\mathrm{U,M}) \quad (7)$$

This index represents the global intensity of preference between the Mark and Unmark decision. Equation (8) is then used to rank the alternatives as positive, negative and complete ranking flows.

$$\begin{cases} \text{Positive outranking flow: } \varphi^{+}(\mathrm{M}) = \pi(\mathrm{M,U});\ \varphi^{+}(\mathrm{U}) = \pi(\mathrm{U,M}) \\ \text{Negative outranking flow: } \varphi^{-}(\mathrm{M}) = \pi(\mathrm{U,M});\ \varphi^{-}(\mathrm{U}) = \pi(\mathrm{M,U}) \\ \text{Complete ranking: } \varphi(\mathrm{M}) = \varphi^{+}(\mathrm{M}) - \varphi^{-}(\mathrm{M});\ \varphi(\mathrm{U}) = \varphi^{+}(\mathrm{U}) - \varphi^{-}(\mathrm{U}) \end{cases} \quad (8)$$

In the Equation (8), if complete ranking $\varphi(\mathrm{M}) > 0$, it is indicated that positive flow prevails while considering marking the crosswalks, and if $\varphi(\mathrm{U}) < 0$, it is indicated that negative flows prevail while considering unmarking the crosswalks. The mark or unmark preference percentages are defined for final decisions in Equations (9) and (10). Final preference scores present the likelihood of using a marked crosswalk versus an unmarked crosswalk to enhance pedestrian mobility and safety. If the difference between two final scores is less than 20%, engineering judgment is highly recommended. This threshold was advocated as a neutral zone by the engineers from Reno and Henderson in Nevada during the guideline field application to remind the decision makers that there is not a big difference between marking and unmarking and then other treatments might be considered.

$$\text{If } \varphi(\mathrm{M}) > 0 \begin{cases} \text{Mark Preference Percentage } \mathrm{F(M)} = \frac{(1+\varphi(\mathrm{M}))}{2} \times 100\% \\ \text{Unmark Preference Percentage } \mathrm{F(U)} = 1 - \mathrm{F(M)} \end{cases} \quad (9)$$

$$\text{If } \varphi(\mathrm{U}) > 0 \begin{cases} \text{Mark Preference Percentage } \mathrm{F(M)} = 1 - \mathrm{F(U)} \\ \text{Unmark Preference Percentage } \mathrm{F(U)} = \frac{(1+\varphi(\mathrm{U}))}{2} \times 100\% \end{cases} \quad (10)$$

Additionally, the guideline recommends considering treatment combinations (e.g., red signal, beacon devices, etc.) and possible roadway design elements (e.g., median refuge island, curb extension, etc.) for pedestrians crossing high-speed, high-volume roadways at unsignalized intersections. Table 5 presents the decision thresholds for additional recommendations and the corresponding explications can be found in Figure 1.

TABLE 5 Final Decisions and Recommendations

Decision Thresholds	Criteria and Critical Thresholds	Final Decision	Additional Recommendations
$\mathrm{F(M)} - \mathrm{F(U)} \geq 20\%$	a U b U c	Mark	Treatment Combinations
$\mathrm{F(U)} - \mathrm{F(M)} \geq 20\%$	a U d	Unmark	Other Design Elements
$\lvert\mathrm{F(U)} - \mathrm{F(M)}\rvert < 20\%$	e	Engineering Judgment	Treatment Combinations and Roadway Design Elements

Note: a. $SL \geq 40mph$; b. $TV \geq 1{,}200vph$; c. $PV \geq 20\ peds/hr$; d. $PRC \geq 2$; e. Combinations of variables C2-C10; U-Union of criteria.

The computational engine of the guideline is implemented using Visual Basic for Application (VBA) programming in EXCEL. The guideline comprises three subsections: (i) Input Phase containing available information of the study site; (ii) Calculation Phase containing inner analysis of response and explanatory factors; and (iii) Output Phase containing the final preference decision.

An illustrative example is presented next to demonstrate the practicability and feasibility of the proposed guideline. The study site is the unsignalized intersection at N Virginia St. & 17^{th} St. in Reno, Nevada. The pedestrian crosswalk was unmarked at this location until this study was conducted. A three hour data collection and observation was conducted on Tuesday, December 6, 2011. The basic study site information is summarized in Table 6 and the detailed analysis procedure is presented in Figure 1.

TABLE 6 Study Site Information

N Virginia Street & 17th Street, Reno, Nevada	Information
Current Crosswalk Condition	Unmarked crosswalk
Geometry Layout of Intersection	3-Leg unsignalized intersection
Number of Travel Lanes	2 Lanes in each direction
Available Gaps	15 Minutes data collected were divided into 5 minutes intervals and the number of average available gaps is 3
Distance to Nearby Crosswalk	466 ft. to N Sierra Street & US 395 intersection
Vehicle Speed Limit	Posted speed limit equals 35 mph
Traffic Volumes	1098 vph during PM peak hour
Pedestrian Volumes	36 peds/hr during P.M. peak hour
Pedestrian Accident Occurrence	2 acc./5 yrs with one occurred in 2008 and the other in 2012

As demonstrated in Figure 1, the ranking scores were calculated automatically by the computation engine. The weight for each variable is the value for the special case when the policy preference factor is not considered as displayed in Table 2. Since the global out-ranking of marking $\varphi(M)$ is greater than 0, the positive flows prevail while considering marking the crosswalk. The output result shows that the preference score for marking this crosswalk is 70% which is 40% higher than the unmark preference. Hence, the guideline recommends marking this pedestrian crosswalk considering all the potential influence factors. Furthermore, since the pedestrian volume during the peak hour is greater than 20, the guideline suggests considering different treatment combinations at this location according to Table 5. This result matches the decision made by the local agency. Shortly after this case study was conducted, a marked pedestrian crosswalk was installed at that location in March 2012. A pedestrian crossing sign was then installed in May 2012. In short, the developed analysis interface is quite user friendly and easy to manipulate as demonstrated in the example above. Agencies can easily adopt this product to analyze local intersections; given adjustments can yield dramatic differences.

Reset

Input Phase	Variables Abb.		Evaluation	Input
	C1	PPT	0-N/A;1-Conservative;2-Moderate;3-Aggressive	
	C2	MOU	0-Unmarked Crosswalk; 1-Marked Crosswalk	
	C3	GL	3-Legs; 4-Legs	
	C4	NTL	1-lane, 2-lanes, 3-lanes, 4-lanes, etc.	
	C5	AG	Unit: number	
	C6	DNC	Unit: feet. (ft)	
	C7	SL	Unit: miles per hour (mph)	
	C8	TV	Unit: vehicles per hour (vph)	
	C9	PV	Unit: pedestrians per hour (peds/hour)	
	C10	PRC	Unit: accidents per year (acc./5 yrs)	

Run

Compute Phase	Input Variables		Weights	$P_i(d)$		Multi-Criteria Index	
				Mark	Unmark		
	PPT					$\pi(M,U)$	$\pi(U,M)$
	MOU						
	GL					$\varphi^+(M)$	$\varphi^-(M)$
	NTL						
	AG					$\varphi^+(U)$	$\varphi^-(U)$
	DNC						
	SL					$\varphi(M)$	$\varphi(U)$
	TV						
	PV					$F(M)$	$F(U)$
	PRC						

Output Phase	Output Results	Mark	Unmark	EJ
	Preference Score			
	Recommendations	**MARK**	**UNMARK**	**EJ**
		Treatment Combination[i]	Other Design Elements[ii]	Monitoring[iii]

i. **Marked crosswalk is recommended.** Additionally, treatment combinations should be considered, including (1) red signal or beacon devices (e.g., HAWK), (2) "active when present" warning devices (e.g., flashing beacons or crossing flags), and (3) enhanced and high-visibility signs and markings.
ii. **Unmarked crosswalk is recommended.** Additionally, other design elements should be considered, including (1) median refuge island, (2) curb extension, and (3) adequate nighttime lighting.
iii. **Engineering Judgment (EJ) is recommended.** The study site should be monitored and if necessary the treatment combinations stated in "i" should be considered along with marked crosswalk.

(a)

Reset

Input Phase	Variables Abb.		Evaluation	Input
	C1	PPT	0-N/A;1-Conservative;2-Moderate;3-Aggressive	0
	C2	MOU	0-Unmarked Crosswalk; 1-Marked Crosswalk	0
	C3	GL	3-Legs; 4-Legs	3
	C4	NTL	1-lane, 2-lanes, 3-lanes, 4-lanes, etc.	4
	C5	AG	Unit: number	3
	C6	DNC	Unit: feet. (ft)	466
	C7	SL	Unit: miles per hour (mph)	35
	C8	TV	Unit: vehicles per hour (vph)	1098
	C9	PV	Unit: pedestrians per hour (peds/hour)	36
	C10	PRC	Unit: accidents per year (acc./5 yrs)	2

Run

Compute Phase	Input Variables		Weights	$P_i(d)$		Multi-Criteria Index	
				Mark	Unmark		
	PPT	0	N/A			$\pi(M,U)$	$\pi(U,M)$
	MOU	0	0.0263				
	GL	3	0.0304			$\varphi^+(M)$	$\varphi^-(M)$
	NTL	4	0.0477				
	AG	3	0.1339			$\varphi^+(U)$	$\varphi^-(U)$
	DNC	466	0.1069				
	SL	35	0.2112			$\varphi(M)$	$\varphi(U)$
	TV	1098	0.0536				
	PV	36	0.1982			$F(M)$	$F(U)$
	PRC	2	0.1918				

Output Phase	Output Results	Mark	Unmark	EJ
	Preference Score			
	Recommendations			

i. **Marked crosswalk is recommended.** Additionally, treatment combinations should be considered, including (1) red signal or beacon devices (e.g., HAWK), (2) "active when present" warning devices (e.g., flashing beacons or crossing flags), and (3) enhanced and high-visibility signs and markings.
ii. **Unmarked crosswalk is recommended.** Additionally, other design elements should be considered, including (1) median refuge island, (2) curb extension, and (3) adequate nighttime lighting.
iii. **Engineering Judgment (EJ) is recommended.** The study site should be monitored and if necessary the treatment combinations stated in "i" should be considered along with marked crosswalk.

(b)

Reset

Input Phase	Variables Abb.		Evaluation	Input
	C1	PPT	0-N/A;1-Conservative;2-Moderate;3-Aggressive	0
	C2	MOU	0-Unmarked Crosswalk; 1-Marked Crosswalk	0
	C3	GL	3-Legs; 4-Legs	3
	C4	NTL	1-lane, 2-lanes, 3-lanes, 4-lanes, etc.	4
	C5	AG	Unit: number	3
	C6	DNC	Unit: feet. (ft)	466
	C7	SL	Unit: miles per hour (mph)	35
	C8	TV	Unit: vehicles per hour (vph)	1098
	C9	PV	Unit: pedestrians per hour (peds/hour)	36
	C10	PRC	Unit: accidents per year (acc./5 yrs)	2

Run

Compute Phase	Input Variables		Weights	$P_i(d)$		Multi-Criteria Index	
				Mark	Unmark		
	PPT	0	N/A	0.0000	0.0000	$\pi(M,U)$	$\pi(U,M)$
	MOU	0	0.0263	0.5333	0.0000	0.56409	0.16105
	GL	3	0.0304	0.6108	0.0000	$\varphi^+(M)$	$\varphi^-(M)$
	NTL	4	0.0477	0.7505	0.1239	0.56409	0.16105
	AG	3	0.1339	0.0000	0.8052	$\varphi^+(U)$	$\varphi^-(U)$
	DNC	466	0.1069	0.0000	0.3500	0.16105	0.56409
	SL	35	0.2112	1.0000	0.0000	$\varphi(M)$	$\varphi(U)$
	TV	1098	0.0536	1.0000	0.0000	0.40304	-0.40304
	PV	36	0.1982	1.0000	0.0500	$F(M)$	$F(U)$
	PRC	2	0.1918	0.1705	0.0000	0.70152	0.29848

Output Phase	Output Results	Mark	Unmark	EJ
	Preference Score			
	Recommendations			

i. **Marked crosswalk is recommended.** Additionally, treatment combinations should be considered, including (1) red signal or beacon devices (e.g., HAWK), (2) "active when present" warning devices (e.g., flashing beacons or crossing flags), and (3) enhanced and high-visibility signs and markings.
ii. **Unmarked crosswalk is recommended.** Additionally, other design elements should be considered, including (1) median refuge island, (2) curb extension, and (3) adequate nighttime lighting.
iii. **Engineering Judgment (EJ) is recommended.** The study site should be monitored and if necessary the treatment combinations stated in "i" should be considered along with marked crosswalk.

(c)

Reset

Input Phase	Variables Abb.		Evaluation	Input
	C1	PPT	0-N/A;1-Conservative;2-Moderate;3-Aggressive	0
	C2	MOU	0-Unmarked Crosswalk; 1-Marked Crosswalk	0
	C3	GL	3-Legs; 4-Legs	3
	C4	NTL	1-lane, 2-lanes, 3-lanes, 4-lanes, etc.	4
	C5	AG	Unit: number	3
	C6	DNC	Unit: feet. (ft)	466
	C7	SL	Unit: miles per hour (mph)	35
	C8	TV	Unit: vehicles per hour (vph)	1098
	C9	PV	Unit: pedestrians per hour (peds/hour)	36
	C10	PRC	Unit: accidents per year (acc./5 yrs)	2

Run

Compute Phase	Input Variables		Weights	$P_i(d)$		Multi-Criteria Index	
				Mark	Unmark		
	PPT	0	N/A	0.0000	0.0000	$\pi(M,U)$	$\pi(U,M)$
	MOU	0	0.0263	0.5333	0.0000	0.56409	0.16105
	GL	3	0.0304	0.6108	0.0000	$\varphi^+(M)$	$\varphi^-(M)$
	NTL	4	0.0477	0.7505	0.1239	0.56409	0.16105
	AG	3	0.1339	0.0000	0.8052	$\varphi^+(U)$	$\varphi^-(U)$
	DNC	466	0.1069	0.0000	0.3500	0.16105	0.56409
	SL	35	0.2112	1.0000	0.0000	$\varphi(M)$	$\varphi(U)$
	TV	1098	0.0536	1.0000	0.0000	0.40304	-0.40304
	PV	36	0.1982	1.0000	0.0500	$F(M)$	$F(U)$
	PRC	2	0.1918	0.1705	0.0000	0.70152	0.29848

Output Phase	Output Results	Mark	Unmark	EJ
	Preference Score	70%	30%	—
	Recommendations	**MARK**	—	—
		Treatment Combination[i]	—	—

i. **Marked crosswalk is recommended.** Additionally, treatment combinations should be considered, including (1) red signal or beacon devices (e.g., HAWK), (2) "active when present" warning devices (e.g., flashing beacons or crossing flags), and (3) enhanced and high-visibility signs and markings.
ii. **Unmarked crosswalk is recommended.** Additionally, other design elements should be considered, including (1) median refuge island, (2) curb extension, and (3) adequate nighttime lighting.
iii. **Engineering Judgment (EJ) is recommended.** The study site should be monitored and if necessary the treatment combinations stated in "i" should be considered along with marked crosswalk.

(d)

FIGURE 1 Case study demonstration: (a) reset the guideline; (b) input available information; (c) run the guideline; (d) final preference score and recommendations.

CASE STUDY

The proposed guideline was applied in a case study involving 32 unsignalized intersections in Nevada to compare actual pedestrian crosswalk types with guideline proposals. From the study sites selected, 50% have marked crosswalks on the major streets and the other 50% have unmarked ones. All marked crosswalks at selected sites belong to the same type, i.e. continental crosswalk, which is a high-visibility type of pedestrian crosswalk. The City of Henderson provided basic intersection information and vehicular and pedestrian volume counts in 2010 at their 24 locations, and field data collection was conducted in the 8 Reno locations in 2011.

Currently, Reno has a relatively balanced number of marked versus unmarked crosswalks, whereas Henderson has a higher percentage of unmarked crosswalks. Agencies will have differences in their preference and policies with respect to pedestrian crosswalks. Therefore, different policy preference tendencies were assigned to the two study areas at first to check whether the proposed guideline can reflect the actual preference. By comparing the existing condition with the guideline recommendation, it indicated that Henderson has a higher percentage matching the aggressive judgment as shown in Figure 2. The matching result of Reno yet suggests that local agencies tend to hold a moderate attitude when it comes to crosswalk markings.

Furthermore, the corresponding preference tendency values were applied to the thirty-two study sites. Both results from the developed guideline and the FHWA guideline were compared with actual field conditions. On the one hand, approximate 73% of all guideline proposals matched actual field data. There were three reasons explaining the difference. Firstly, there was no consideration regarding pedestrian-related crash factors in either Reno or Henderson agencies when the crosswalks were installed. However, the pedestrian crash record is a very important factor in the proposed guideline. Secondly, although both agencies currently took volume into account, it is more important to consider potential factors simultaneously and comprehensively as documented in the new guideline. Thirdly, the final preference scores are not divided into two absolute categories, mark and unmark, but the engineering judgment category is highly recommended when the difference between the two final scores is less than 20%. This category is not included in real world data.

On the other hand, about 60% of all recommendations based on the FHWA guideline confirm actual crosswalk types. At the same time, around 64% of proposed guideline results met FHWA recommendations. Nevertheless, if merely considering combinations of vehicle ADT, speed limit, and number of travel lanes which are the core of the FHWA guideline, the developed guideline (labeled as This Study* in Figure 3) will provide very close results as the FHWA guideline. By complementing pedestrian volume, crash data and engineer preference factors, the developed guideline could accommodate more practical and insightful suggestions pertaining to crosswalk types.

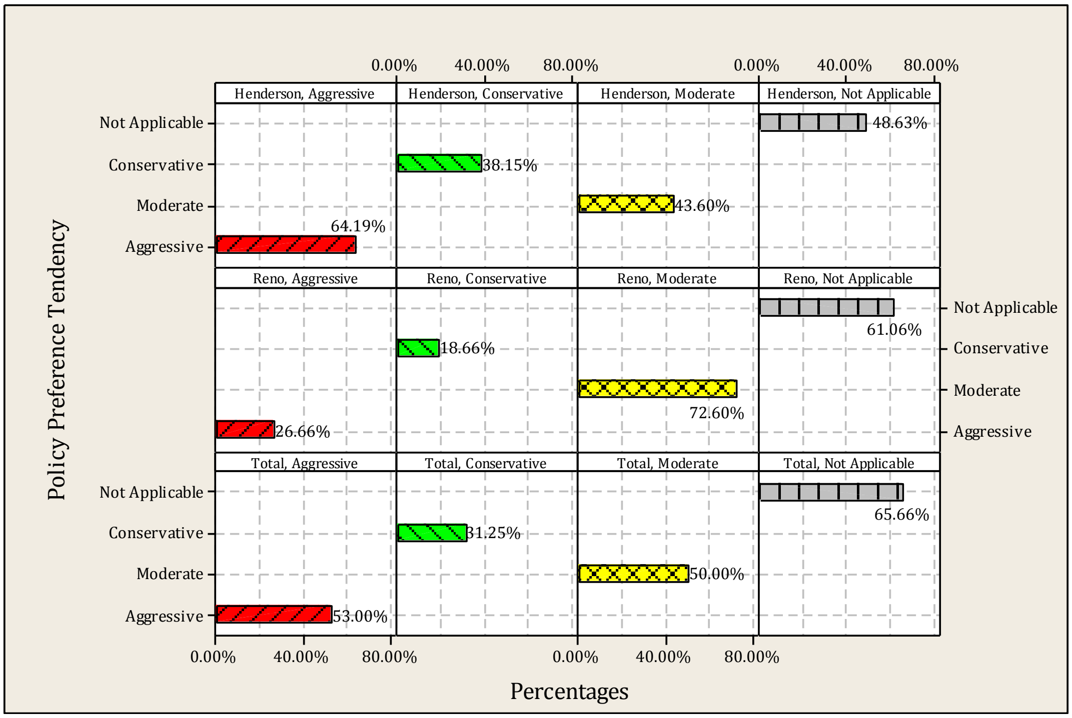

FIGURE 2 Preference match results.

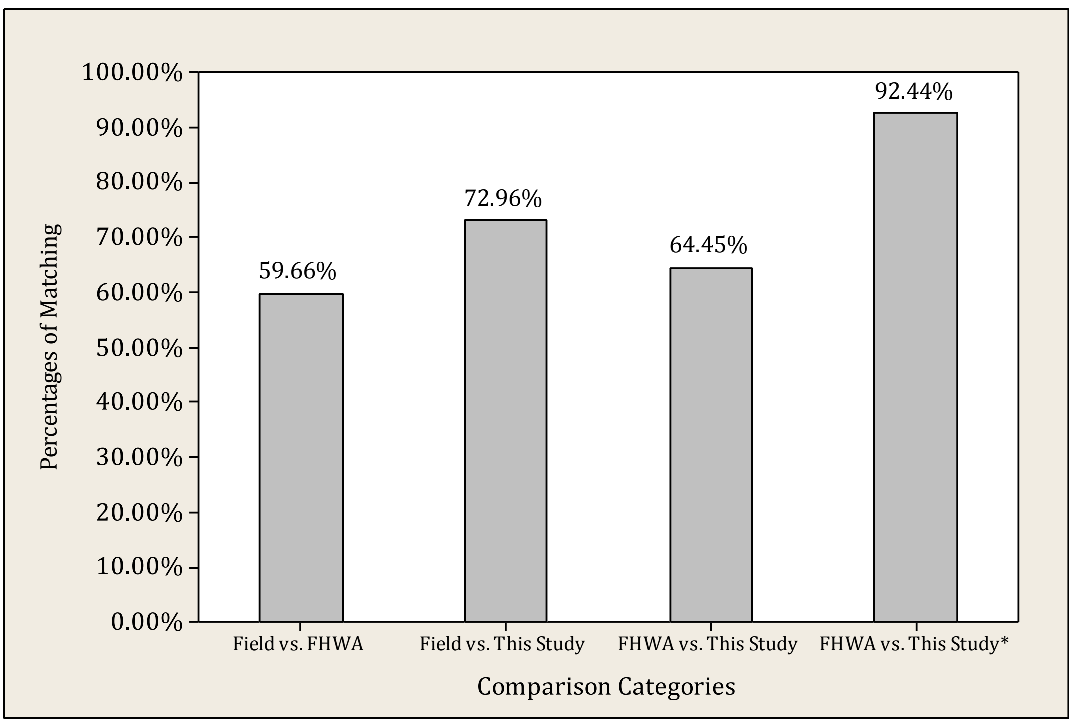

FIGURE 3 Comparisons of field data, developed guideline and FHWA guideline.

SUMMARY AND CONCLUSIONS

Pedestrian crosswalk marking is a useful traffic control device, but it is very important to realize the positive as well as the negative consequences of marking crosswalks. From the mobility point of view, marked crosswalks may seem to increase pedestrian mobility, but with perhaps a deceived sense of security. In fact, most studies conducted previously indicated more pedestrian crashes at marked crosswalks than unmarked crosswalks. It is believed that such results vary by location and by jurisdictions. The inconsistencies about the safety merits of marking crosswalks indeed put the government and public into a dilemma. Thus, this study proposed a new guideline to direct the installation of crosswalk markings considering both mobility and safety contributing factors.

Crosswalk installation is a typical multi-criteria problem as discussed in this study. Therefore, the proposed guideline follows a combination of basic multi-criteria methodologies namely the PROMETHEE and the AHP approaches and incorporates key elements such as traffic and pedestrian volumes, geometry of the location, vehicle speed limit, and pedestrian related crash records. The guideline was implemented using VBA programming in Excel which can be easily adapted by any agency and jurisdiction. Model calibration will by all means be needed to make sure it reflects specific location situations. In this research effort, case studies were conducted to verify the practicability and feasibility of the proposed guideline. The comparison results indicate that the new guideline can easily help engineers make sound decisions for the placement of marked crosswalks and interpret the dilemma of crosswalk markings. Future studies using analogous methodologies to develop guidelines that can be used to select other pedestrian crossing treatments for unsignalized intersections are worth exploring.

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