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SPECIAL ISSUE

A methodology to assess pedestrian crossing safety

Olga Basile · Luca Persia · Davide Shingo Usami

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Abstract
Purpose The safety level of a pedestrian crossing is affected by infrastructure characteristics and vehicular and pedestrian traffic level. This paper presents a methodology that allows assessing the safety level of a pedestrian crossing, regulated or not by traffic light, in an urban area according to the features of the crossing.
Methods A hierarchical structure representing factors influencing crossing safety has been developed and the relative contributions of each factor were calculated using AHP method. A composite index for crossing safety and specific indexes for main aspects included in the assessment have been developed.
Results Main assessment aspects are: Spatial and Temporal Design, Day-time and Night-time Visibility and Accessibility. Night-time Visibility resulted to have the higher weight (about 41%).
Conclusion Developed indexes allow ranking of pedestrian crossings and assigning intervention priorities, highlighting the aspects which are to be enhanced. The methodology has been used for the evaluation of 215 pedestrian crossings in 17 European cities for the Pedestrian Crossing Assessment Project co-financed by FIA Foundation.

Keywords Pedestrian crossing · Safety index · Assessment · AHP

O. Basile · L. Persia · D. S. Usami (✉)
CTL—Centro di ricerca per il Trasporto e la Logistica,
Sapienza Università di Roma,
Via Eudossiana,
18 – 00184, Rome, Italy
e-mail: davideshingo.usami@uniroma1.it

1 Introduction

In 2008, pedestrian fatalities represented 21% of all road traffic fatalities in Europe (24 EU Member States).[1] Although decreasing at European level, in countries like Poland and Romania pedestrian fatalities show an increasing trend and a higher percentage of fatalities (up to 35%).

According to different studies [12, 15], pedestrian accidents occur most frequently at street crossing, and often, especially for older pedestrians, at pedestrian facilities like a zebra crossing. A research by FHWA [20] shows that pedestrian crossings are not sufficient to cross safely, if not integrated with adequate equipment.

Many studies can be found about pedestrian accidents characteristics [12, 19], pedestrian's and driver's behaviour at crossings [3, 4, 6, 9, 17] and evaluation of measures enhancing pedestrian crossings safety [7, 13].

The safety level of a road element can be assessed in three different ways [1]: accident frequency or similar, surrogate measures about road user behaviour or opinions by experts or road users.

By relating these indicators with a mix of factors affecting crossing safety, a model can be developed.

In the case of pedestrian crossings, models using road accidents are few [20] because of the rarity of pedestrian crashes at a given location. Carter et al [1] developed a model based on behavioural data and opinions to estimate a pedestrian safety index related to crossings and intersections. Other existing models define a safety related index for a generic traffic environment: crossing difficulty [3, 10], or level of service of pedestrian facilities [8], or "walkability" of pedestrian environment [2].

[1] Source: www.erso.eu

There are several before/after studies that have estimated the variation of accident frequency or safety related indicators consequent to the introduction of specific measures [7, 13, 18]. However the relationship and the relative importance of many factors and features are still unclear.

This paper presents a methodology that allows assessing the safety level of pedestrian crossings in urban area based on an on-site inspection performed using ad-hoc data gathering forms. In detail, the research question relates to how to assign a safety rate to a pedestrian crossing on the basis of its various features and characteristics in order to define a priority list of interventions and to suggest which features need to be improved, as the specific contribution of a crossing feature to pedestrian safety level has been defined.

The approach undertaken consists in: problem definition and selection of safety evaluation criteria, weighting of criteria, definition of a composite indicator that expresses the safety level on the basis of crossing features.

The proposed methodology has been used for the evaluation of 215 pedestrian crossings in 17 European cities for the Pedestrian Crossing Assessment Project co-financed by FIA Foundation.

2 Analysis methodology and main results

2.1 Problem definition

Safety of a pedestrian facility depends on its features and on how it is used (i.e. pedestrian and vehicles traffic characteristics).

Models existing in literature are based both on traffic and pedestrian volumes information and on pedestrian crossing features, but in many cases traffic data are not available. The chosen approach focuses on safety of a pedestrian crossing, without taking into account existing traffic composition and volumes.

The risk is therefore not to select for intervention pedestrian crossings that show a high accident frequency due to higher traffic volumes. On the other hand the methodology permits to identify for intervention pedestrian crossings showing the worst characteristics.

A number of factors exist from literature that affect directly or indirectly pedestrian crossing safety. The relative weight of each factor can be defined through opinions by a panel of experts. The problem of finding the specific contribution of each factor to safety has been solved applying Analytic Hierarchy Process (AHP) method proposed by Saaty [14].

This method is generally used to compare different alternatives and evaluating which one is the best to satisfy a defined goal. For the purpose of the paper, AHP has been used to aggregate different experts' opinions about contribution of every factor to safety.

A theoretical framework for safety has been defined including potential crossing safety related factors/features. Factors and features have been selected by a panel of experts on the basis of their relevance, perceived by the panel, and of results found in literature.

Due to significant differences in traffic rules and road users behaviour between signalized and not signalized pedestrian crossings, these two scenarios have been treated separately.

For each scenario the problem has been decomposed into three hierarchical levels. The first level represents the pedestrian crossing safety composite index.

The second level is defined by four macro-criteria contributing to safety of pedestrian crossings:

- Spatial and Temporal Design,
- Day-time Visibility,
- Night-time Visibility,
- Accessibility.

The third level contains the assessment criteria related to each of the four macro-criteria (see not signalized pedestrian crossings case in Fig. 1 and signalized pedestrian crossings case in Fig. 2).

Macro-criteria have been defined grouping identified criteria according to common objectives of good design principles [5, 16].

Spatial and Temporal Design macro-criterion takes into account pedestrian exposure to traffic, conflicts and timing factors to assess the functioning of the crossing for the pedestrian. Included criteria aim at minimizing waiting time needed to find a crossing opportunity and time needed to cross safely for all road users, including limitation of traffic exposure, through the reduction of conflict points and segmentation of crosswalk.

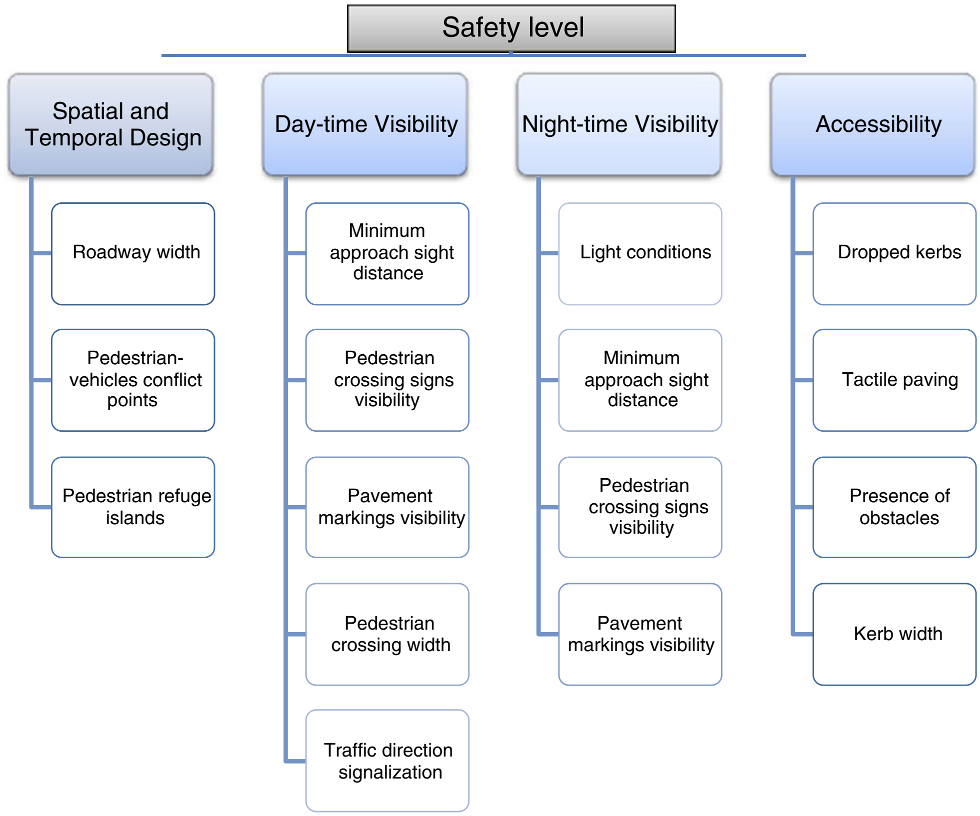
Day-time Visibility and Night-time Visibility criteria evaluate visibility of pedestrians at crossing for motorists, visibility of the pedestrian crossing for motorists, and visibility of oncoming vehicles for pedestrians.

Accessibility criteria account for ensuring proper access for all road users, with or without disabilities, to approach the pedestrian crossing free of obstacles and possible dangers.

For each criterion a specific indicator has been identified. Indicators can refer to quantitative measures (e.g. roadway width) or qualitative measures (e.g. visibility conditions of pavement markings).

As different measurement units are present, indicators have been re-scaled in order to have a common range (0, 1). A value near to 0 is associated to safer situations, while a value near 1 is associated to risky situations.

Fig. 1 Hierarchical structure for not signalized pedestrian crossings



For quantitative measures, re-scaling consisted in giving a distance from a reference value or in definition of indicators above or below a threshold. For qualitative measures, categorical scales that assign a score to possible indicator values have been used. Engineering design handbooks and research studies provide conditions for safe and correct design of a pedestrian crossing [5, 7, 11, 16].

Selected criteria and related indicators are presented in Table 1.

2.2 Weighting of criteria

Once the problem has been defined, AHP has been used to find a weight for each criterion present in the theoretical framework.

According to this method, in case of a hierarchal structure with three levels defined by J criteria, M macro-criteria and a goal, it is necessary to evaluate:

- The weight w_j^m of general criterion A_j associated to general macro-criterion C_m;
- The weight w_m of general macro-criterion C_m contributing to the general goal (safety level).

All the weights are calculated by aggregating the results from a number of pairwise comparison square matrices, where the elements *aij* of a matrix (also called "dominance coefficients") represent the prevalence of criterion Ai on criterion A_j in reference to the corresponding macro-criterion/goal. A comparison matrix (like that in Table 2) needs to be defined for each of the four macro -criteria and for the general goal.

The prevalence is measured qualitatively using a semantic scale [14] that links a numerical value (from 1 to 9) to a judgment expressing a possible result from the comparison (Table 3).

A focus group of 15 experts, with previous experience in infrastructure design, road safety planning and evaluation, has been set up to perform pairwise comparisons. Each expert assessed the relative importance of criteria individually to avoid possible influence on judgments.

Assuming $ajk = wj/wk$, with wj the weight associated to criterion j and wk the weight of criterion k, the following are valid:

- $ajj=1$
- $akj=1/ajk$ (Mutuality relation: necessary to guarantee the symmetry of prevalence judgments)
- $aji*aik = ajk$ (Consistency relation)

The weights of each criterion have been obtained aggregating the dominance coefficients of resulting comparison matrices through the geometric mean, obtaining the "aggregated comparison matrix" $\underline{\underline{A}}$.

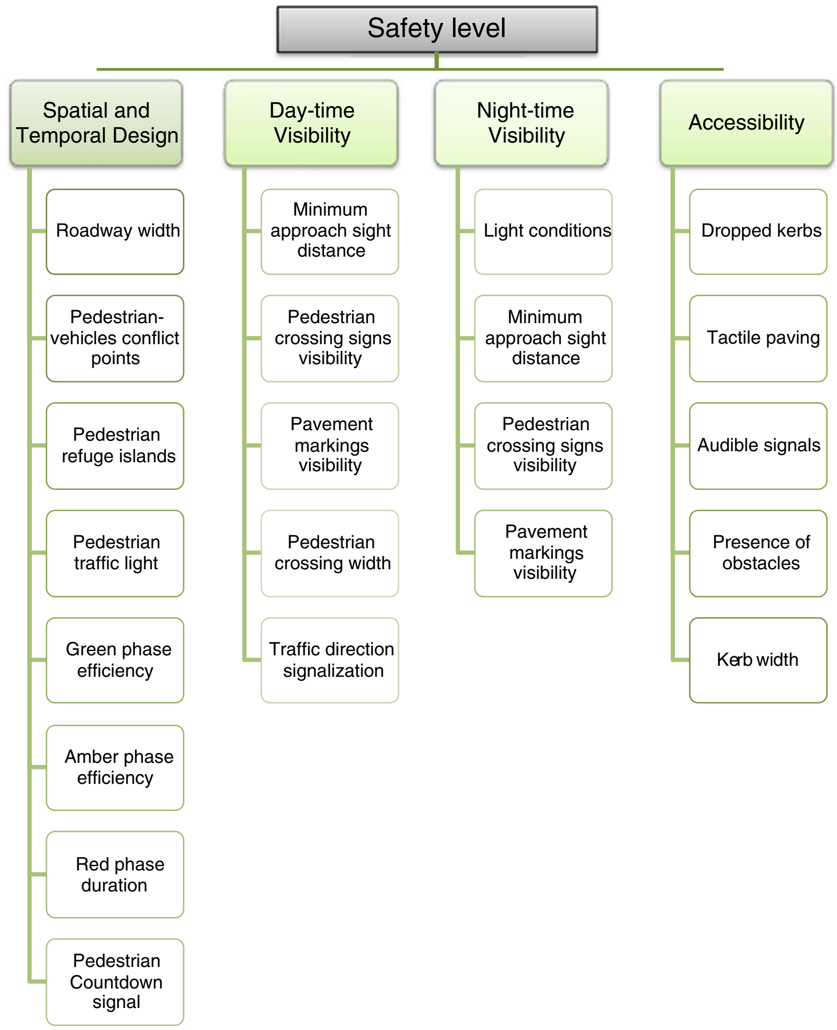


Fig. 2 Hierarchical structure for signalized pedestrian crossings

Matrix $\underline{\underline{A}}$ should be square, positive, symmetric and consistent. Given $\underline{w}$ the vector of the weights *wi*, it can be demonstrated that:

$$\underline{\underline{A}}\ \underline{w} = n\underline{w} \tag{1}$$

From (1) it is possible to say that $\underline{w}$ is the eigenvector of matrix $\underline{\underline{A}}$ associated with the eigenvalue n. If matrix $\underline{\underline{A}}$ is consistent, it admits only one solution: the eigenvalue *lmax,* whose value is equal to *n*.

However in most cases, judgments given by experts need to be verified through the calculation of the Consistency Index proposed by Saaty.

According to AHP method a square matrix $\underline{\underline{A}}$ can be considered consistent if the Consistence Ratio *CR* is lower than 0,1:

$$CR = \frac{CI}{RI} < 0,1 \tag{2}$$

Where:

- $CI = \frac{l_{\max} - n}{n-1}$ is called Consistency Index: in case of perfect consistence ($l_{\max}$ = n) CI=0;
- RI is called Random Index. It represents the average value of CI for a square, symmetric and positive matrix of order n random generated; values o f RI are known in function of n.

Finally, given a comparison matrix $\underline{\underline{A}}$, if CR <0,1, than the calculated weights w_i can be considered equal to vector components $\underline{w}$ associated to the maximum eigenvalue l_{max}.

If CR >0,1, the deviation of the matrix $\underline{\underline{A}}$ from the condition of perfect consistence is judged not admissible, a revision of subjective judgments is needed. Results from the application of AHP method show that Night-time Visibility account for over 40% in both scenarios. Weights distributions among the four macro-criteria for the two scenarios are shown in Fig. 3. Night-time Visibility resulted to have the higher weight in

Table 1 Criteria and range values of related indicators

CRITERIA	Range values
Spatial and temporal design	
Roadway width	0: <=2.75 m; otherwise (1–2.75/width)
Pedestrian-vehicles conflict points	0.2: 1 conflict point; 0.4: 2 conflict points; 0,6: 3 or 4 conflict points; 1: >4 conflict points
Painted or raised pedestrian refuge islands (also designed for disabled people)	0: refuge island width >1.5 m; 0.5:refuge island width<=1.5 m; 1: no refuge island
Pedestrian traffic light	0: Yes; 1: No
Green phase efficiency	0: phase sufficient for mobility disabled people; 0,5: phase sufficient for people without disabilities; 1: phase not sufficient
Amber phase efficiency	0: phase sufficient for mobility disabled people; 0,5: phase sufficient for people without disabilities; 1: phase not sufficient
Red phase duration	0: <=60 sec; 1:>60 sec
Pedestrian Countdown signal	0: Present; 1: Not present
Day-time visibility	
Minimum approach sight distance	0: sight distance > brake distance; 1: sight distance < brake distance
Pedestrian crossing signs visibility	0: Very good; 0,25: Good; 0,5: Sufficient; 0,75: Unsatisfatory; 1: Poor
Pavement markings visibility	0: Very good; 0,25: Good; 0,5: Sufficient; 0,75: Unsatisfatory; 1: Poor
Pedestrian crossing width	0: >2,5 m; 1: <2,5 m
Traffic direction signalization	0: Present; 1: Not present
Night-time visibility	
Light conditions	0: Very good; 0,25: Good; 0,5: Sufficient visibility; 0,75: Unsatisfatory visibility; 1: Poor visibility
Minimum approach sight distance	0: sight distance > brake distance; 1: sight distance <brake distance
Pedestrian crossing signs/signal visibility	0: Very good; 0,25: Good; 0,5: Sufficient; 0,75: Unsatisfatory; 1: Poor
Pavement markings visibility	0: Very good; 0,25: Good; 0,5: Sufficient; 0,75: Unsatisfatory; 1: Poor
Accessibility	
Dropped kerbs	0: Present; 1: Not present
Tactile paving	0: Present; 1: Not present
Audible signals	0: Present; 1: Not present
Presence of obstacles	0: Not present; 1: Present
Kerb width	0: kerb width >2 m; 1: kerb width <2 m

both scenarios (about 41%), followed by Day-time Visibility, Spatial and Temporal Design and Accessibility.

In Table 4 the relative weights associated to each criterion and calculated Consistency Ratio for all aggregated matrices in both scenarios are reported. All values are smaller than 0,1, this indicates coherence of judgments provided by the experts.

In Fig. 4 global weights assigned to each criterion are presented. In both considered scenarios, Night-time Light conditions, Night-time Minimum approach sight distance and Day-time Minimum approach sight distance account for about 43% to crossing safety. For not signalized pedestrian crossings (NSPC) other important factors are: presence of pedestrian refuge islands, pedestrian- vehicles conflict points and obstacles in approaching crossing. For signalized pedestrian crossings (SPC) scenario, Night-time Pavement markings visibility, Presence of obstacles, Day-

Table 2 Example of comparison matrix

	A1	...	Ak	...	AJ
A1	...	...	...	...	...
...	...	...	...	...	...
Aj	...	...	ajk	...	...
...	...	...	...	...	...
AJ	...	...	...	...	...

Table 3 Saaty semantic scale

Aij	Judgement
1	Equal important
3	W eak importance
5	Strong importance
7	Very strong importance
9	Absolute importance
2,4,6,8	Intermediate values

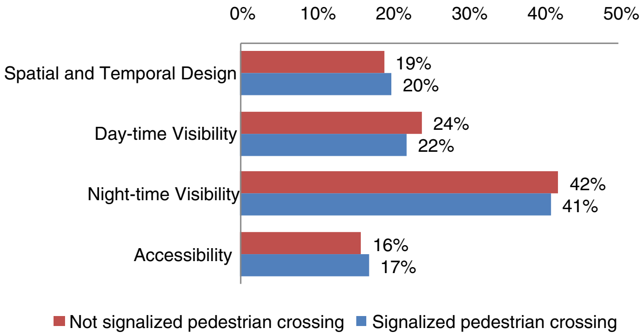


Fig. 3 Weights related to macro-criteria

time Pavement markings visibility and Night-time PC signs/signal visibility are also important.

2.3 Composite safety index

A composite index for crossing safety and indexes for each macro-criterion have been developed. For the determination of indexes, the following assumptions have been made:

- the safety level of a pedestrian crossing is calculated through a weighted mean;
- relationship among criteria has not been taken into account (i.e. combination of effects from two or more criteria has not been considered).

The proposed index is defined by:

$$\text{Safety index} = \sum_m w_m \cdot \sum_j \left(w_j^m \cdot A_j \right)$$

Where:

- w_j^m is the weight of general criterion A_j associated to general macro-criterion C_m;
- w_m is the weight of general macro-criterion C_m contributing to the general goal.

Table 4 Relative weights and Consistency Ratios (CR) for not signalized pedestrian crossings (NSPC) and signalized pedestrian crossings (SPC)

CRITERIA	Weights (NSPC)	Weights (SPC)	CR NSPC	CR SPC
Perceived Safety			0,024	0,004
Spatial and Temporal Design		20%	0,014	0,019
Roadway width	15%	7%		
Pedes trian-vehicles conflict points	42%	12%		
Painted or rais ed pedes trian refuge is lands (als o des igned for dis abled people)	43%	14%		
Pedes trian traffic light	–	22%		
Green phas e efficiency	–	18%		
Am ber phas e efficiency	–	14%		
Red phas e duration	–	7%		
Pedes trian Countdown s ignal	–	6%		
Day-time visibility	24%	22%	0,034	0,030
Minim um approach s ight dis tance	48%	48%		
Pedes trian cros s ing s igns vis ibility	17%	18%		
Pavem ent m arkings vis ibility	21%	20%		
Pedes trian cros s ing width	5%	5%		
Traffic direction s ignalization	9%	9%		
Night-time visibility	42%	41%	0,004	0,006
Light conditions	47%	42%		
Minim um approach s ight dis tance	29%	34%		
Pedes trian cros s ing s igns /s ignal vis ibility	11%	11%		
Pavem ent m arkings vis ibility	13%	13%		
Accessibility	16%	17%	0,004	0,003
Dropped kerbs	26%	22%		
Tactile paving	19%	16%		
Audible s ignals	–	20%		
Pres ence of obs tacles	38%	3%		
Kerb width	17%	12%		

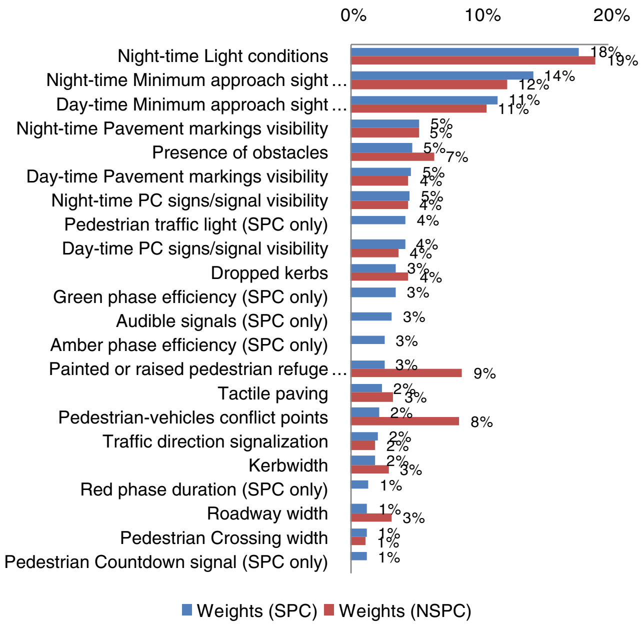


Fig. 4 Global weights for SPC and NSPC

Additional indexes have been developed to evaluate safety of a pedestrian crossing in relation to a single macro-criterion. The index, for a generic macro- criterion *m* is defined by:

$$\text{Macro} - \text{criterion Index} = w_m \sum_j w_j^m \cdot A_j$$

A Micro-criterion Index $= w_j^m A_j$ for criterion j can be also specified in order to identify features and characteristics to be enhanced.

A scale defined by five classes has been developed to classify pedestrian crossings in relation to the index value calculated with the proposed methodology.

3 Methodology testing and application

Through the application of the methodology to a group of pedestrian crossings it is possible to order them by calculated safety level and get information both on pedestrian crossings that need to be redesigned and aspects that should be enhanced (through Macro and Micro-criteria indexes).

Two data gathering forms have been developed to collect information about signalized and not signalized pedestrian crossings. The forms include also two diagrams in order to guide the inspector in measuring main elements and visibility conditions. As an example, reference diagram for main elements of a pedestrian crossing is reported in Fig. 5. Required measurements are identified by letters (related codes present in the form are reported in parenthesis) and address to: a—Pedestrian crossing width (10.I); b—Distance between bus stop and crossing center line (10.F); d—Distance between crossing center line and nearest sight obstruction (10.B); l—Pedestrian island / median width (9.F); L—Crossing distance (10.D); o—Sight obstruction width (10.C).

A complete inspection is performed in two phases, with daylight and during night hours, and it takes about 30 min. Data collected can be input into a spreadsheet that performs all necessary calculations to get results about overall crossing safety and at macro-criteria level. For each pedestrian crossing the determined result is a number between 0 and 1, falling in a class of Table 5.

For testing purposes a sensitivity analysis to examine the criteria that have more relevance on the safety level determination has been carried out using data gathered for a group of pedestrian crossings of the city of Parma (Italy). The selected area belongs to the city centre, inside this area there is a public park, some important transport facilities and other points of interest. A group of 15 crossing was evaluated and the rankings considering Safety index and Macro-criterion indexes were elaborated. An analysis of changes of the ranking by removing a macro-criterion one by one was performed.

In the first column of Table 6, ranking by total safety level is reported, the other columns report ranking without "Spatial and temporal design", "Day-time Visibility", "Night-time Visibility" and "Accessibility" respectively.

Fig. 5 Reference diagram for main elements measures

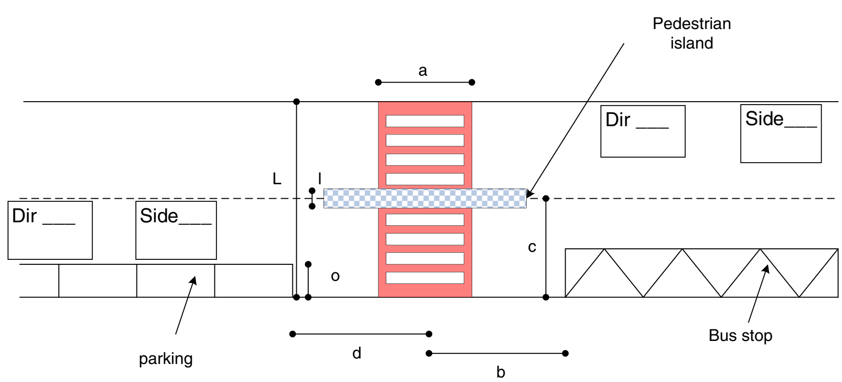


Table 5 Scale of pedestrian crossing safety level

Level of safety	Numerical value
Excellent	0,00–0,20
Good	0,21–0,40
Sufficient	0,41–0,60
Unsatisfactory	0,61–0,80
Poor	0,81–1,00

White cells point out an unchanged position compared to "Total Safety" ranking, light grey cells represent a shifting of one or two positions compared to "Total Safety" ranking while dark grey cells display a shifting of three or more positions compared to "Total Safety" ranking.

The table shows that most of dark grey cells are in the Accessibility column. This means that major changes to the ranking are caused by removing Accessibility from the methodology, even if a lower weight has been assigned to this macro-criterion. A high number of changes is produced also by removing "Spatial and temporal design" macro-criterion, but the entity of modification to the ranking is less deep.

Changes linked to Accessibility can be explained by the dispersion of indexes values. In fact, observing arithmetic mean and variance calculated for safety values and for macro-criteria indexes related to the 15 crossings, the largest value of variance belongs to Accessibility.

Even if "Night-time Visibility" received the main contribution to crossing safety level, "Accessibility" seems to be the macro-criterion that causes a deeper modification of the ranking. In fact, the higher variance resulted to belong to "Accessibility" values, while "Night-time Visibility" has the lower variance.

4 Conclusions

The paper has presented a methodology that provides a quantitative evaluation of pedestrian crossing safety level through a composite index, highlighting less safe aspects.

The value of the proposed methodology is mainly its usability as it can be applied in absence of traffic data, which are often difficult to find, especially in case of pedestrian traffic.

Table 6 Changes to safety level ranking by removing macro-criteria

Ranking by Safety level	Ranking Without "Spatial and temporal design"	Ranking Without "Day-time Visibility"	Ranking Without "Night-time Visibility"	Ranking Without "Accessibility"
A1	A1	A1	A1	A1
A2	A4	A2	A2	A2
A3	A5	A3	A3	B1
A4	B1	A4	A4	B4
A5	B2	A5	A5	B5
B1	A2	B1	B2	A3
B2	A3	B5	C4	B2
B3	B3	B3	B1	B3
B4	B4	B2	B3	A5
B5	C1	B4	B5	C1
C1	B5	C1	C1	A4
C2	C2	C3	B4	C2
C3	C4	C2	C2	C3
C4	C3	C5	C3	C4
C5	C5	C4	C5	C5

(white)	Same position compared to Safety level ranking
(light grey)	Shifting of 1 or 2 positions compared to Safety level ranking
(dark grey)	Shifting of 3 or more positions compared to Safety level ranking

Within a project co-financed by FIA Foundation data from 215 pedestrian crossings across 17 European capitals have been collected.

All investigated pedestrian crossings have been selected from specific urban city areas. City areas are required to respect a number of aspects to guarantee a similar urban context. City areas selection takes into account: presence of at least a tourist point of interest (museums, churches, etc.), presence of important public transport facilities such as underground stations or main bus or tramway stops, presence of traffic critical points (school area, commercial area, roundabouts, etc.), not prevalence of pedestrian areas, a circle length of 2/3 km.

Rankings of the 215 crossings by safety index and by macro-criteria indexes have been carried out.

For every investigated city a file with a summary of results has been developed. Analysis with proposed methodology highlighted some common issues present at European level such as: absence of pedestrian refuge islands, improper traffic light timing, car parking blocking visibility and frequent accessibility problems due to obstacles on pedestrian crossing.

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