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COMPARATIVE ANALYSIS OF PEDESTRIAN ACCIDENTS RISK AT UNSIGNALIZED INTERSECTIONS

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Abstract. More than one accident of three that involve pedestrians in urban area occurs at road intersections. The users' inproper behaviour, the geometrical characteristics of the intersections, and the high speeds of vehicles are the main causes of pedestrian accidents. In this field, the procedures of road safety analysis (Road Safety Audit and Road Safety Review) play a fundamental role: they are the techniques of investigation aimed at identifying the safety issues and the possible improvements. Nowadays, however, the safety analysis does not allow a quantitative assessment of the level of safety regarding pedestrians. The objective of this work, is to propose a procedure for the quantitative risk analysis. The first phase of the study has been oriented to the definition of the virtual schemes associated with the possible configurations for unsignalized intersections in urban areas, predominantly characterized by local roads. The urban areas in which the residential function prevails, while it is poorly available in the circulation function, were considered then. The criteria, aimed at the characterization of the level of safety, offered to pedestrians by the real urban intersections, have been developed in the second phase. For this purpose, three categories of information have been useful: 1) the data describing the geometry characteristic of the intersection; 2) the geometric characteristic of road elements responsible of the functional pedestrian protection; 3) vehicular and pedestrian traffic data.

Keywords: road intersections, safety, urban road, accidents data, virtual scheme, risk level.

1. Introduction

The problem related to the accidents involving pedestrians is widespread all over the world. It is known that pedestrians, defined as "vulnerable users", are particularly exposed to the accident risk with motor vehicles (Chen *et al.* 2013; Gitelman *et al.* 2012; Prato *et al.* 2012; Zegeer, Bushell 2012). Milligan *et al.* (2013) showed a comparison of different criteria for estimation of the risk of pedestrian accidents.

Many studies are based on statistical analysis of pedestrian accident data, in order to identify the causes of accidents and, consequently, provide countermeasures. In particular, using various techniques of statistical analysis (Bayesian Multivariate Poisson Regression, Log-Normal Regressions, Binary Logistic Regression, etc.), it has been possible to define the main variables that affect the occurrence of accidents between vehicles and pedestrians, both, in urban and in suburban area (Clifton *et al.* 2009; Ha, Thill 2011; Luoma, Peltola 2013; Moudon *et al.* 2011; Siddiqui *et al.* 2012). This has allowed the researchers to propose solutions to improve pedestrians' safety both, through infrastructure design and through other strategies for improvement.

The actions to improve the safety of pedestrians aim to reduce the severity of the consequences in case of collision between vehicle and pedestrian. Kelly *et al.* (2009) examined the impact of personal and environmental characteristics on severity of injuries sustained in pedestrian–vehicle crashes using a generalized ordered probit model.

Badea *et al.* (2010) have described the development of a multivariate model that is able to detect the most influential parameters on the consequences of vehicle-pedestrian collision and to quantify their impact on pedestrian fatality risk. Fredriksson and Rosén (2012) investigated the potential pedestrian head injury reduction from hypothetical passive and active countermeasures compared to a vehicular integrated system. The active countermeasure was an autonomous braking system, which had been activated one second before the impact if the pedestrian was visible to a forward-looking sensor. Mohammadipoura and Alavi (2009) attempted to optimize the geometric cross-section dimensions of raised pedestrian crosswalks (RPC) employing safety and comfort measures which reflect environmental conditions and drivers behavioural patterns.

The road intersections are real "black spots" for pedestrian accidents. These issues were addressed mainly in the case of signalized intersections. The researches by Pulugurtha and Sambhara (2011), and Miranda-Moreno

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et al. (2011) propose forecasting models based on input parameters deduced from the geometric characteristics and functional properties of signalized intersections (e. g., socioeconomic characteristics, accessibility to public transit systems, and road network characteristics as the number of lanes, speed limit, and pedestrian and vehicular volume).

Other studies also analysed the influence of weather conditions. In particular, the purpose of the Li and Fernie (2010) study was to determine whether pedestrian behaviour becomes more risky in inclement weather through the investigation of street crossing behaviour and compliance under different weather and road surface conditions at a busy two-stage crossing. Other research, such as the work of Alhajyaseen *et al.* (2012), studied the dangers of the left turn manoeuvre, which is traditionally the most hazardous. The proposed method consists of four empirically developed stochastic sub-models, including a path model, free flow speed profile model, lag/gap acceptance model, and stopping/clearing speed profile model.

Ren *et al.* (2012) quantified the degree of safety of crosswalks at signalised intersections and estimated the accident risk as a function of vehicular conflicts: the SMOK clustering algorithm based on the fuzzy cluster analysis method was used. The human factor, associated with the irregular behaviour of pedestrians, is thoroughly studied by King *et al.* (2009). Crossing against the lights and crossing close to the lights both exhibited a crash risk per crossing event approximately eight times than the legal crossing at signalised intersections.

According to the latest ISTAT (Italian Institute of Statistics) data, in 2011, 15.1% of the 3860 people, killed on Italian roads, are pedestrians, while the remaining 84.9% are car drivers (69.7%) and passenger vehicles (15.3%). These data assume a greater significance, when it is considered that pedestrians have the highest severity index (2.71).

Table 1. The unsafe conditions for pedestrians in urban road intersections (Canale *et al.* 2009)

No.	Type of condition
1.	Crosswalks length wider than 10 m (without interruption)
2.	Possibility of crossing the intersection area at each point
3.	Reduced mutual visibility driver/pedestrian because of the geometrical configuration of the intersection and/or because of visual obstructions
4.	High speed approach at the intersection by motorized vehicles
5.	Presence of vehicles parked near the intersection area
6.	Crosswalks located away from the edge of the intersection
7.	Poor visibility of crosswalks at night
8.	Crosswalks are not adequately signalized
9.	Absence of sidewalks or presence of sidewalks with inadequate width
10.	Presence of numerous attraction poles for pedestrians (shops, banks, public offices, etc.)
11.	Crosswalks located away from the public transit stops in the intersection area
12.	Presence of driveways near pedestrian crossings

Another aspect that has to be pointed out, concerns the contexts in which collisions occur between vehicles and pedestrian. More than 95% of accidents occur in urban areas and about 35% of them occur at the intersections.

The acquired knowledge of this research group during many years of study on urban road safety has identified the main issues of pedestrian safety at intersections. In particular, in Table 1, the conditions are synthetically reported. That area is able to increase the dangerousness of the road intersections and consequently reduce the levels of pedestrians' safety.

An important role in defining the dangerousness of the road intersections for pedestrians is played by the Road Safety Audit and Road Safety Review procedures. These techniques of investigation aim at identifying safety problems and the proposition of possible decisive countermeasures.

Nowadays, the Road Safety Audit and Road Safety Review procedures allow the preparation of the qualitative judgments only. The objective that the authors intend to obtain, is the development of a procedure for a quantitative estimate of the risk level, offered by the linear road intersections, based on an original technique for comparing schemes of real road intersections, and "virtual schemes" organized to ensure the highest standards of a pedestrian safety.

2. Methodology approach

The proposed method for the estimation of the safety level offered by urban intersections of the linear type is based on an original process of comparison between the real intersections and the series of virtual schemes, characterized by all the requirements that have been able to optimize the performance of a pedestrian's safety. Essentially, the determination of the safety level of a specific intersection will be carried out through the comparison between the examined intersection and the corresponding virtual scheme. The differences between the two schemes are quantified by means of a numerical score for each element, the magnitude of which are indicative of the safety level provided to pedestrians. With the proposed method, both the risk exposure of pedestrians through the values of vehicular and pedestrian flow, and safety aspects associated with the visibility characteristics of the intersection are considered, including parameters directly related to the overall geometric shape of the intersection area.

This procedure is mainly valid to urban residential areas, mostly characterized by local roads. Circulation is not the predominant function and, therefore, the speed is very small (less than 30 km/h to a maximum of 40 km/h), and it is also possible to equip the road intersections with elements that drastically reduce the speed of motor vehicles (curb extension, raised crosswalks, etc.). The proposed procedure is carried out through the following steps:

1) defining the schemes of virtual intersections;

2) determining the safety factors to be attributed to the components of the intersections that are useful to optimize the level of a pedestrian's safety;

3) introducing the adjustment factors for the quantification of the effects on safety, induced by conditions of visibility at the intersection;

4) introducing the adjustment factors associated with the level of risk exposure;

5) giving the analytical definition of the risk level of pedestrians accidents.

2.1. Virtual schemes for road intersections

The method for defining the virtual schemes is based on a criterion, specially elaborated, defined "principle of minimizing the risk of pedestrian accident". This criterion is expressed as: *the ideal configuration of the area of intersection, both geometrically and regarding the organization of the elements of urban design, that is consistent with the spatial and functional constraints, minimizes the risk of a collision between vehicles and pedestrians*.

All the design features that presence in the intersection areas is an advantage for the protection of pedestrians are shown in Table 2.

With the rational combination of these countermeasures, it is possible to define the so-called "virtual schemes", which represent the optimal configurations of the areas of intersection that satisfy the principle of minimizing the risk of pedestrian accidents. A compositional criterion, based on the assembly of a series of six legs-types, equipped with the design features, listed in Table 2, has been chosen for the assembly of the virtual schemes.

The possible legs-type, indicated with the letters A trough F, which differ in the width of the cross section (greater or less than 10 m) and in a way to prevent the illegal parking near the intersection area, are represented in Fig. 1.

The virtual schemes that are used in the procedure of comparison with the real intersections have to be made up through the composition of the legs-type. The composition has to be carried out following the analysis of the real scheme, with reference to the intersection object of analysis. Firstly, it is necessary to evaluate the main geometrical (width of the individual legs) and functional (width of the area i.e. to allow or not the irregularly parked vehicles) characteristics. Secondly, to assemble the virtual corresponding scheme, choosing the branches-type consistent with the peculiar features that are mentioned above.

Note that all the legs-type, each other, are not the solutions of alternative design, each leg-type is a modular element that has uniquely to be used in the process of composition of the possible virtual schemes. For instance, the schemes C and D, as well as all the others, define two different design conditions that are not interchangeable. The leg-type indicated with the letter C represents a mode of avoid parking (curb extension) that also acts as a device for reducing the length of crosswalk, while the branch-type named D provides means to avoid parking (bollards) and to reduce the length of the crosswalks obtained through the pedestrian refuge islands. The design of the leg-type D differs from the leg-type C just in the realization of the curb extension. It has happened because of the road width of the leg-type D, in which the curb extension is not able to reduce sufficiently (less than 10 m) the width

Table 2. Design features for pedestrian safety at intersections (Canale *et al.* 2009)

No.	Type of countermeasures
1.	Raised crosswalks
2.	Crosswalks located near the traffic attractors
3.	Crosswalks near the edge of the intersection area
4.	Bus stops placed near the crosswalks
5.	No driveways placed at the crosswalks
6.	Deterrents for pedestrian crossing
7.	Pedestrian refuge islands
8.	Curb extensions in order to reduce the length of the crosswalks (<10 m)
9.	Parking bollards
10.	Artificial lighting
11.	Sidewalks with adequate width
12.	Appropriate signs and markings on the pavement (paints, coatings, etc.)

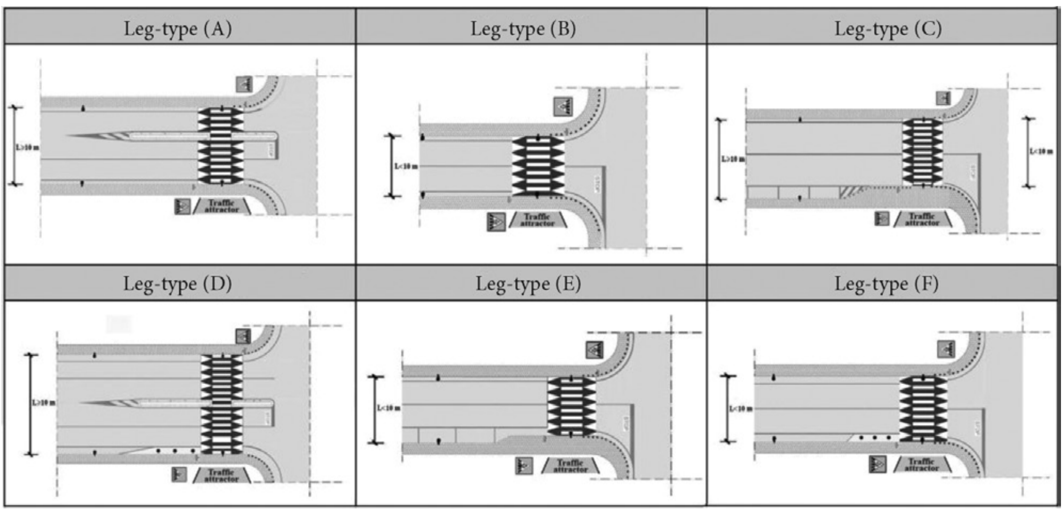

Fig. 1. Legs-type for the composition of the virtual schemes

of the crosswalk. The legs-type E and F, both have a road width of less than 10 m but differ in the organization of parking lots. The E scheme ensures the regular parking up of a certain extent, and, then, presents a system of deterrence of parking near the centre of the intersection. The F scheme, by contrast, provides only the parking deterrence near the crosswalk and does not allow the realization of regular stalls for parking. It is evident that the choice of one of the solutions depends on the need to ensure or not the parking lots arranged linearly on the approach legs to the intersection. This possibility is also strongly influenced by the width and the overall organization of the road section.

The example of Section 2.6. shows how to reach the composition of the virtual schemes.

2.2. Safety factors analysis

For estimating the "weights" to be attributed to each of the countermeasures aimed at improving pedestrians' safety at intersections, criterion, based on the effectiveness adequately documented of these actions, in terms of reduction in accident rates related to pedestrians in the urban context, have been chosen. This has sometimes been done "directly", using the data in the literature, regarding the efficiency of the single action or the specific countermeasure. Another times it was necessary to act "indirectly", by processing the data on pedestrian accidents through reasonable assumptions about the reducing of accident rates for effect of the realization of the design actions shown in Table 2.

The accidents data in Italy published by ISTAT, referring to the period between 2008 and 2011 is used for the definition of safety factors. The other used data was reported in *NCHRP 500 REPORT: Volume 10: 2008 A Guide for Reducing Collisions Involving Pedestrians*, in *The Handbook of Road Safety Measures* by Elvik *et al.* (2009), and in *Progettare la sicurezza stradale (Designing Road Safety)* by Canale *et al.* (2009). Additional information has been taken from another documents listed in the bibliography.

Table 3 shows the accident data, expressed as a percentage of the total, relating to accidents occurring in urban areas, where pedestrians were involved. The reference period is 2008/2011. The last column of the table shows the mean values in the whole reference period. The data

Table 3. ISTAT data on pedestrian accidents (2008–2011 years)

Causes of accident	Accident data, %				
	2008	2009	2010	2011	Mean
Car speed	18.27	15.26	15.03	15.05	15.90
Vehicle against traffic	1.24	1.23	1.44	0.97	1.22
Vehicles that have passed moving vehicles	1.04	1.00	1.15	1.09	1.07
Vehicles in manoeuvring	9.11	8.03	9.24	8.58	8.74
Vehicles that have not respected the signal	2.52	2.66	2.06	2.48	2.43
Vehicles exit from a driveway	0.43	0.48	0.49	0.44	0.46
Vehicle that is out of the roadway	0.91	0.71	0.89	1.09	0.90
Vehicle that did not respect the pedestrian precedence on the crosswalks	30.72	32.17	33.20	34.55	32.66
Vehicles that have passed the vehicles stopped to allow the pedestrian crossing	1.04	0.94	0.83	0.79	0.90
Impact between vehicle load and pedestrian	0.75	0.63	0.51	0.76	0.66
Vehicles that have passed a stopped tram	0.56	0.50	0.44	0.42	0.48
Defects or damage of the vehicle	0.11	0.12	0.11	0.10	0.11
Abnormal physical or mental condition of the driver	0.65	0.83	0.89	0.87	0.81
Pedestrian who walked in the wrong direction	0.47	0.35	0.34	0.52	0.42
Pedestrian who walked in the middle of the road	3.43	4.49	4.30	4.26	4.12
Pedestrian who was standing, lingering or playing on the road	1.95	1.70	1.56	1.96	1.79
Pedestrian who worked on the roadway not protected by a sign	0.20	0.11	0.14	0.27	0.18
Pedestrian who climbed on the moving vehicle	0.12	0.32	0.14	0.22	0.20
Pedestrian who descended from vehicle imprudently	0.00	0.02	0.29	0.81	0.28
Pedestrian who unexpectedly came out from behind a parked vehicle	4.16	4.33	5.12	4.62	4.56
Pedestrian who crossed the roadway without respect the rules, at a crosswalk signalized or regulated by police officer	2.71	2.78	2.97	2.97	2.86
Pedestrian who crossed the roadway irregularly	19.61	21.11	18.68	17.08	19.12
Pedestrian drunk	0.11	0.09	0.07	0.14	0.10
Pedestrians who practiced morbid actions	0.00	0.03	0.01	0.00	0.01
Pedestrian struck by sudden illness	0.02	0.01	0.00	0.01	0.01
Pedestrian who had ingested drugs	0.00	0.03	0.01	0.00	0.01

of Table 3 was used to derive, through an indirect logical process, the effectiveness of design features that has not been possible to classify in function of the decreasing accident rate induced by their realization. Eg, the efficiency of the devices of deterrence for pedestrians crossing is estimated considering that their installation is the potential reduction of accidents due to three causes:

1) pedestrians who cross the roadway irregularly;
2) pedestrians who walk in the middle of the road;
3) pedestrians who stand, linger or play on the road.

Since the three causes above are responsible, on average, for 25% of accidents involving pedestrians in urban areas, it is reasonable to say that the potential effectiveness of bollards for crosswalks, in terms of reducing accident rates, is equal to 25%.

The deduction of the effectiveness of artificial lighting of crosswalks located in urban intersections has been based on a study conducted in Perth (Australia), which results have been published in *NCHRP REPORT 500: Volume 10: 2008 A Guide for Reducing Collisions Involving Pedestrians*. According to this study, the percentage of reduction of night-time accidents which involve pedestrians were amounted to 62%. Since the average of night-time pedestrian accidents that occur in urban areas are around 20% of the total of a day, it is clear that the presence of an efficient system of artificial illumination in the intersection areas leads to an abatement of about 12% of the total accidents, compared to the operating conditions of intersections without any lighting at night.

Once determined, for each of the twelve features reported in Table 2, the value of the percentage reduction of the pedestrian accident rate has been possible to proceed by arranging the above-mentioned features in order of decreasing effectiveness and comparing the reduction rate for each of them with the last value. The matrix of safety factors (C_s) reported in Table 4 has been obtained in this way.

For each of the possible schemes, obtained by means of the virtual composition procedure, described in Section 2.1, it is possible to calculate the score (P_v), as the sum of the safety factors associated with the features included in the specific scheme. The presence of more than one countermeasure of the same type (eg a series of raised crosswalks) will be computed by averaging the safety factors characteristic of each specific feature.

2.3. Adjustment factor to visibility conditions

The factors defined in the previous section, allow to characterise the level of safety that is provided for pedestrians by the elements of functional organizations of the road intersections. The geometrical shapes of the intersections and the boundary elements play an important role in influencing the performance of a pedestrian safety. Particularly, the geometric dimensions of the legs (width, angle, radius of turn) and the characteristics of crosswalks (length, distance from the intersection, position perpendicular or diagonal), along with the presence of lateral obstacles, influence a decisive way of the mutual visibility vehicle-pedestrian.

Considering the mutual visibility between vehicle and pedestrian, the most unfavourable condition usually occurs when, because of the presence of obstacles in the right margin of the road, the driver of the vehicle who turns right has the visual field partially or totally clogged, and, consequently, he is not able to display properly the pedestrians on the crosswalk (especially in the first part of the longitudinal development of the crosswalk).

Fig. 2 shows some examples of visibility conditions related to:

– crosswalk orthogonally disposed at a certain distance from the intersection centre in the absence and presence of an obstacle lateral (Figs 2a, 2b);
– crosswalk disposed in diagonal in the absence and presence of an obstacle lateral (Figs 2c, 2d);
– leg of intersection inclined at an angle different from 90° in the absence and presence of an obstacle lateral (Figs 2e, 2f).

With reference to the schemes of Figs 2a, 2c, and 2e, it is possible to note that the condition of optimal visibility is when the driver has the overall vision of the crosswalk. This condition is expressed by the following geometric equality:

$$L_v = L_{ap}, \tag{1}$$

where L_{ap} – length of the crosswalk portion, which is located in the lane, is occupied by the vehicle that is turning to the right, is expressed in meters. It coincides with the length of the segment AB, shown in Fig. 2; L_v – length, expressed in meters, of the base of the triangle shown in Fig. 2. Coherently with the Italian legislation consisting in *D.M.* 19/04/2006 *Norme funzionali e geometriche per la costruzione delle intersezioni stradali* [Functional and Geometric Guidelines for the Design of Road Intersections],

Table 4. Matrix of safety factors

No.	Type of measure	Safety factor
1.	Raised crosswalks	17
2.	Deterrents for crossing pedestrians	8
3.	Crosswalks near the edge of the intersection area	6
4.	Pedestrian refuge islands	6
5.	Crosswalks located near the traffic attractors	6
6.	Bus stops placed near the crosswalks	6
7.	Curb extensions in order to reduce the length of the crosswalks (<10 m)	5
8.	Parking bollards	4
9.	Artificial lighting	4
10.	Sidewalks with adequate width	2
11.	Appropriate signs and markings on the pavement (paints, coatings, etc.)	1
12.	No driveways placed at the crosswalks	1

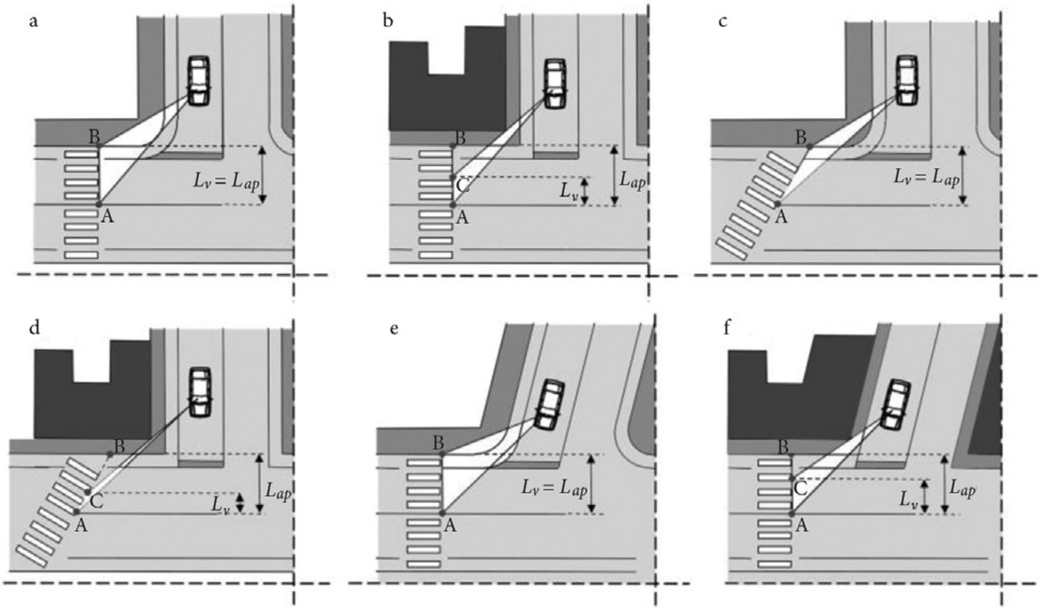

Fig. 2. Conditions of visibility between pedestrians and vehicles in the road intersections

Table 5. Adjustment factor to visibility conditions

Reference condition	Risk level	Adjustment factor
$L_v/L_{ap} = 1$	Not significant	1.00
$2/3 \le L_v/L_{ap} < 1$	Low	1.10
$1/3 \le L_v/L_{ap} < 2/3$	Medium	1.30
$L_v/L_{ap} < 1/3$	High	1.50

the vertex of the triangle coincides with the driver's eye and it is located 3 m from the stop line for the intersection controlled by STOP sign or 20 m for intersection controlled by the yield sign. In the case of main legs (no controlled by stop sign or yield signal), the vertex is located at the distance of arrest by the crosswalk. The triangle sides coincide with the two segments that join the vertex, respectively, with an endpoint of the segment of length L_{ap} (point A), and the point C, obtained as the intersection between the AB segment, and the line passing through the eye of the car driver oriented according to the maximum possible angle that allows to intercept the AB alignment without the interposition of transversal obstacles. The segment AC, therefore, coincides with the segment AB, only if there are no obstacles to the vision of the crosswalk for drivers of motor vehicles.

The schemes of Figs 2b, 2c and 2f, show the case in which, due to the presence of a building at the edge of the intersection area (common situation in the urban contests), the length of segment AC is less than the length of segment AB. In this situation, therefore, there is a condition indicative of a visual deficiency and, consequently, a situation of the potential danger for pedestrians who are crossing the roadway. This condition is geometrically expressed by the following relationship:

$$L_v < L_{ap}. \tag{2}$$

On the basis of the considerations made above, a criterion, designed to take into account the higher level of risk for pedestrians in situations where the visibility conditions at intersections show significant deficiencies, has been developed. This criterion, which is summarized in Table 5, provides the adjustment factors for the visibility (F_v) as a function of the ratio between the lengths L_v and L_{ap}. In particular, four levels of risk, gradually increasing, associated with conditions of reduction of visibility between vehicle and pedestrian have been defined.

Since the problems of mutual visibility between vehicle and pedestrian are potentially present on all legs of the same intersection, the *total adjustment factor for the visibility* was introduced, obtained as a weighted average of the individual adjustment factor and deduced from Table 5, as a function of pedestrian flows, typical of pedestrian crossings, and present on the legs of the intersection. This factor ($F_{v(T)}$) has the following analytical expression:

$$F_{v(T)} = \frac{\sum_{y=1}^{B} F_{vy} Q_{py}}{\sum_{y=1}^{B} Q_{py}}, \tag{3}$$

where $F_{v(T)}$ – a total adjustment factor to visibility conditions; F_{vy} – an adjustment factor to visibility conditions, deduced from Table 5 for the y-leg of intersection; B – a number of the intersection legs; Q_{py} – pedestrian flow per hour (peak hour) traveling on the crosswalk located to the right of the y-leg.

2.4. Adjustment factor to risk exposure

Numerous researches in the literature provide interesting correlations between the level of risk for pedestrians and the amount of traffic flows passing on the crosswalks.

These explorations have identified some uncertainty about the estimate of the actual influence of the quantity of pedestrian flows on the safety level associated with this category of users. Many studies consider negative that the pedestrian flow at a crosswalk is relatively low compared to the vehicular flow. In this case the car drivers, not considering the passage of pedestrians as a probable event, are induced to minimize the level of attention to the vulnerable users, and to adopt speed rather incurred even on the crosswalks. By contrast, another studies show that higher flows, being directly related to the increased exposure to risk of pedestrians, is a factor of safety absence, especially in the crosswalks more transited from motorized traffic. In any case, almost all research on the subject agrees that the increase in vehicular flow is a negative factor to the protection of pedestrians.

Taking into account the observations made above, an adjustment factor which takes into account the risk exposure for pedestrians, according to different classes of vehicle flow (expressed in terms of Annual Average Daily Traffic (*AADT*)) has been developed. To pursue this aim, a study by the Federal Highway Administration (FHWA) in 2002, which provides precise recommendations to enhance the safety of crosswalks at the unsignalized intersections, according to four classes of traffic was used. From these recommendations, Table 6, which shows the adjustment factors (F_e) associated with four levels of risk and dependent on the traffic classes proposed by the FHWA, has been filled.

Even in this case, the *total adjustment factor to risk exposure* has been introduced and obtained as a weighted average of the individual adjustment factor, deduced from Table 6 as a function of pedestrian flows, and typical of pedestrian crossings present on the legs of the intersection. The factor ($F_{e(T)}$) has the following analytical expression:

$$F_{e(T)} = \frac{\sum_{x=1}^{B} F_{ex} Q_{px}}{\sum_{x=1}^{B} Q_{px}}, \tag{4}$$

where $F_{e(T)}$ – total adjustment factor to risk exposure; F_{ex} – adjustment factor to risk exposure, deduced from Table 6 for the x-leg of intersection; B – number of the intersection legs; Q_{px} – pedestrian flow per hour (peak hour) traveling on the crosswalk located on the y-leg.

2.5. Analytical definition of the risk level for pedestrian accidents

The procedural steps set out in the preceding paragraphs have led to the definition of virtual schemes, and the introduction of safety factors, and adjustment factors. It is necessary to explain how the proposed methodology has to be applied. The first step is to quantify the risk level related to the intersection object of analysis and to evaluate the safety performance offered to pedestrians. For this purpose, it is necessary to make the comparison between the real scheme and the corresponding virtual scheme, obtained by the combination of the legs-type, illustrated previously.

From the comparison of the two schemes, partial differences emerge in relation to some features that, in the virtual schemes, are differently designed. Consider, eg, the virtual scheme resulting from the assembly of three legs-types indicated with the letter *a* (it is made up by 3 crosswalks equipped with pedestrian refuge islands). It is possible that the real scheme differs from the virtual scheme only partially. Eg, there will be a real intersection having a crosswalk equipped as in the virtual scheme, another crosswalk devoid of pedestrian refuge islands and another crosswalk provided with curb extension through, which reduces the width of the crosswalk.

The result attributed to the three measures, described above, has, therefore, take into account the heterogeneity in the configuration. This will be done by evaluating the weighted average of the safety factors that are relevant to the features type considered. The weighting has to be carried out as a function of the pedestrian flow (peak hour) which refers to the considered element. It has, then, the following expression:

$$C_{s(N)} = \frac{\sum_{i=1}^{N} C_{si} Q_{pi}}{\sum_{i=1}^{N} Q_{pi}}, \tag{5}$$

where $C_{s(N)}$ – safety factor concerning the series of N elements of the real scheme with heterogeneous characteristics compared to the corresponding series and associated with the virtual scheme; N – number of elements that compose the set of design features of the considered

Table 6. Adjustment factors to exposure and the corresponding risk levels

Type of section	Traffic classes (*ADT*, vpd)							
	≤9000		9000–12 000		12 000–15 000		>15 000	
	Risk level	F_e	Risk level	F_e	Risk level	F_e	Risk level	F_e
Two-lane	Not significant	1.00	Low	1.10	Low	1.10	Low	1.10
Three-lane	Not significant	1.00	Low	1.10	Medium	1.30	Medium	1.30
More than three lanes with median	Not significant	1.00	Low	1.10	Medium	1.30	High	1.50
More than three lanes without median	Not significant	1.00	Medium	1.30	High	1.50	High	1.50

intersection. These measures guarantee the safety of an expected objective (e.g. reduction of the length of the crosswalk) or the modality indicated in the virtual scheme (e.g. pedestrian refuge island), or with different modalities (e.g. curb extension), or it will not be able to ensure the achievement of the expected objective. C_{si} – safety factor for the i-element of the set of N elements in the scheme of real intersection (this factor takes one of the values in Table 4, or assumes the value of zero if the element is not considered to be attributable to any of the safety measures listed in the Table 4). Q_{pi} – pedestrian flow per hour traveling on i-element on the series of N elements of the real scheme.

In conclusion, the characteristic score of the real scheme (P_r) is provided by the following relationship:

$$P_r = \sum_{j=1}^{M} C_j, \quad (6)$$

where M – number of measures, singly or in series, in the real scheme; C_j – safety factor, relative to the j-element present in the real scheme. This factor is inferred from Table 5 for the individual countermeasures. It is estimated by the Eq (5) for the elements in series, it assumes value of zero if the countermeasure does not appear within the matrix of the safety factors (Table 5).

Once known the scores (P_v and P_r) corresponding to the pair of schemes for which the process of comparison has taken place, it is possible to estimate the risk level (L_R) for the scheme of intersection object of study, using the following expression:

$$L_R = \frac{P_v - P_r}{P_v} \cdot 100. \quad (7)$$

The last step of the procedure consists in estimating the Global Risk Level (L_{RG}) for the real intersection. This indicator incorporates the adjustment factors, defined in the preceding paragraphs and evaluated with (3) and (4).

The expression of the L_{RG} is the following:

$$L_{RG} = L_R \cdot F_{v(T)} \cdot F_{e(T)}. \quad (8)$$

According to the values assumed by the parameter L_{RG}, the four risk levels reported in Table 7 have been defined. The last column of the Table 7 provides the recommendations to improve the level of safety offered to pedestrians.

3. Application of the methodology

The application of the developed procedure has been performed on an urban intersection of Catania. It is an intersection made up by four legs from two roads (Ughetti Street and Lago di Nicito Street) both of width less than 10 m, with parking areas, both legal and illegal near the middle of the intersection (Fig. 3).

Table 7. Risk levels of pedestrian accidents for road intersections

Reference condition	Risk level	Recommendations
$L_{RG} < 25$	Not significant	The organization of the intersection is almost optimal. It does not require specific interventions for adaptation.
$25 \le L_{RG} < 50$	Low	The realization of few measures to improve the intersection ensures optimum levels of safety for pedestrians.
$50 \le L_{RG} < 75$	Medium	The countermeasures for adaptation and development of the intersection are relevant. Low-cost interventions decrease the level of risk. The achievement of optimum safety conditions, however, requires considerable economic efforts.
$L_{RG} \ge 75$	High	An intolerable risk level for pedestrians characterizes the intersection. The achievement of an acceptable risk level requires countermeasures for adaptation and development, associated with high implementation costs. It will possibly signalize the intersection, in order to move temporally the conflicts between pedestrians and motor vehicles.

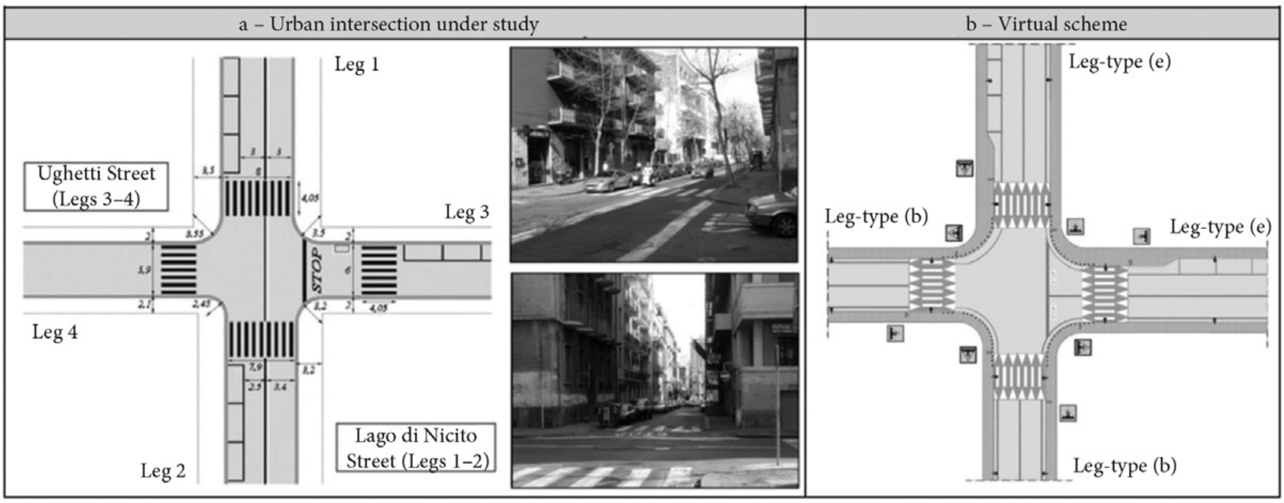

Fig. 3. Case study

Table 8 shows the traffic flows (*AADT*, vpd) and the pedestrian flows per hour (peak hour) for each of the four legs.

Each leg of the intersection has width between 6 m and 8 m, in addition, as showed by the photos of the intersection (Fig. 3a), there is the problem of illegal parking (even above the crosswalks).

The assembly of the virtual scheme, then, has to begin with the selection of those legs which are compatible with the characteristics mentioned above (Fig. 1). In conclusion, the virtual scheme, relative to this case, is represented in Fig. 3b, resulting from the composition of two legs of type *b* and two legs of type *e*.

Table 9 shows the evaluation of the score (P_r), relative to the real scheme, and the comparison with the score (P_v) associated with the virtual scheme.

The adjustment factors are shown in Table 10.

Through the application of Eqs (7) and (8), it is possible to obtain:

$$L_R = \frac{P_v - P_r}{P_v} \cdot 100 = \frac{55-25}{55} \cdot 100 = 54.54$$

and

$$L_{RG} = L_R \cdot F_{v(T)} \cdot F_{e(T)} = 54.54 \cdot 1.00 \cdot 1.07 = 58.36.$$

On the basis of Table 7, the L_{RG} for the intersection object of the study is classifiable as *Medium*.

In the case of the availability of a large financial budget, it will be possible to obtain a Global Risk Level classifiable as *Insignificant*: the countermeasures No. 1 (raised crosswalks) and No. 11 (appropriate signs and markings on the pavement) have to be applied simultaneously on all the intersection legs in order to make L_{RG} below 25. Therefore, in this case $P_r = 43$ and, consequently, the result is:

$$L_R = \frac{P_v - P_r}{P_v} \cdot 100 = \frac{55-43}{55} \cdot 100 = 21.81$$

and

$$L_{RG} = L_R \cdot F_{v(T)} \cdot F_{e(T)} = 21.81 \cdot 1.00 \cdot 1.07 = 23.34.$$

However, an acceptable L_{RG} will be reached, classifiable as *Low*, through the implementation of countermeasures of modest economic burden of type No. 2 (deterrents for crossing pedestrians). In this case $P_r = 33$ and, consequently, the result is:

$$L_R = \frac{P_v - P_r}{P_v} \cdot 100 = \frac{55-33}{55} \cdot 100 = 40.00$$

and

$$L_{RG} = L_R \cdot F_{v(T)} \cdot F_{e(T)} = 40.00 \cdot 1.00 \cdot 1.07 = 42.80.$$

4. Conclusions

1. Through the introduction of the technique of the comparative analysis, it has become possible to quantify the risk of pedestrian accidents at linear intersections of an urban road. The proposed methodology is based on an original procedure of comparison between the real unsignalized intersection and the virtual scheme characterized by the requirements that are necessary to maximize pedestrian safety. The estimate of the level of safety of an intersection is unsignalized, therefore, it is carried out through the comparison between the real intersection and the associated virtual scheme. The differences between the two schemes are quantified by means of a numerical score assigned to each geometric element (leg), component the intersection. Taking this methodology, finally, both the risk exposure of pedestrians and the visibility characteristics of the intersection are considered through a series of parameters related to the intersection geometry.

2. In order to perfecting the methods for safety analysis (Road Safety Audit and Road Safety Review), this research group proposes in the immediate future, not only to refine the methodology of the comparative analysis, but also to extend the applicability of the methodology even at the roundabouts, also considering the global issues related to all categories of users.

3. The possibility of using risk indexes for simple evaluation constitutes an advantage for the analysis of groups that, in addition to a purely qualitative estimate, are in the position to provide a judgment corroborated by numerical parameters. It is useful as well to be able to better support the Administrations in choice of actions of functional adaptation of the roads, which possibly affect the financial budget.

Table 8. Traffic and pedestrian flows at the intersection under investigation

Flow	Leg 1	Leg 2	Leg 3	Leg 4
AADT, vpd	11 000	11 000	8500	1900
Pedestrian flow, ped/h	236	234	228	248

Table 9. Scores of safety indicators for compared schemes

Scheme	Types of countermeasures (Table 5)												Scores
	1	2	3	4	5	6	7	8	9	10	11	12	
	Safety factors												
Real	–	–	6	–	6	6	–	–	4	2	–	1	$P_r = 25$
Virtual	17	8	6	–	6	6	–	4	4	2	1	1	$P_v = 55$

Table 10. Adjustment factors to visibility condition and to exposure of the risk

No.	F_v	$F_{v(T)}$	F_e	$F_{e(T)}$
Leg 1	1.00	1.0	1.10	1.07
Leg 2	1.00		1.10	
Leg 3	1.00		1.00	
Leg 4	1.00		1.00	

It has been shown indeed that the minimum objective of security (Global Risk Level classifiable as *Low*) is obtainable and could be obtained through the application of measures of modest economic burden, and it is not necessarily characterized by a high impact and high constraints on the utilization conditions of the urban road intersections.

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