ANALYSIS OF PEDESTRIAN RISK EXPOSURE IN RELATION TO CROSSING BEHAVIOUR

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ABSTRACT

The objective of this research is the analysis of pedestrians risk exposure along urban trips in relation to pedestrians crossing behavior. First, an appropriate microscopic indicator is selected for the estimation of pedestrians risk exposure while road crossing at isolated locations. This indicator expresses exposure as the number of vehicles encountered by pedestrians during the crossing of a single uncontrolled road lane, and can be further adapted and applied for various road design and traffic control features. Moreover, the number and type of crossings along a pedestrian trip can be identified on the basis of the trip length and topology, whereas the choice set of alternative crossing locations for each crossing decision can also be defined. The crossing probability associated with each alternative location along the trip can be then estimated by means of a sequential logit model. Finally, a method is presented for the estimation of pedestrians exposure along a trip in relation to their crossing behavior. The proposed approach is demonstrated on the basis of a pilot implementation, for a typical pedestrian trip in the centre of Athens, Greece, for four scenarios combining different traffic conditions and pedestrians' walking speed. The results show that pedestrians' exposure along a trip is significantly affected by their crossing choices, as well as by road and traffic characteristics. It is also revealed that pedestrians with increased walking speed may partly compensate for their risk exposure, so that it is not significantly affected by traffic volume. Moreover, specific locations with increased pedestrian risk exposure can be identified for each trip. The proposed microscopic analysis of pedestrian exposure is proved to be advantageous compared to existing macroscopic ones, revealing the different possible definitions and aspects of pedestrians exposure, with useful implications for road safety analysis.

Key-words: road safety; exposure; pedestrians; behaviour.

BACKGROUND AND OBJECTIVES

The majority of pedestrian casualties in road crashes occurs along trips in urban areas, and particularly while road crossing, where pedestrians interact with motorized traffic *(1)*. The analysis of pedestrians risk exposure while road crossing under different conditions along urban trips may contribute towards more efficient and pedestrian-oriented planning and implementation of road design, traffic control and crossing facilities, the more accurate estimation of pedestrians road crash risk in urban areas, and thus to the improvement of pedestrians safety *(2, 3)*. However, existing approaches for estimating pedestrians risk exposure have several limitations, as they are not sufficiently detailed and do not take into account the implications of the crossing behavior and the interaction of pedestrians with vehicles.

Pedestrians road crash risk is most often examined within the framework of macroscopic pedestrian safety analyses *(4)*. The lack of information on pedestrians risk exposure is one of the main limitations of macroscopic road safety analyses internationally *(5, 6)*. The road crash risk of pedestrians is mainly estimated on the basis of macroscopic indicators, such as the number of road crashes or casualties to the population of pedestrians *(7, 8)*, the walking distance travelled *(9)*, the walking time spent *(10)*, the number of trips *(11)* or the number of road crossings *(12, 13)*.

Several research studies underline that macroscopic indicators do not account for important aspects of pedestrians risk exposure *(2, 14, 15)*. For instance, the risk exposure of pedestrians while moving along roads is relatively low, as hit-along-roadway crashes are a minor proportion of pedestrian crashes *(16)*, while the risk exposure while crossing roads and interacting with vehicles is most important. Moreover, the flexibility, adaptability and often risk-taking behavior of pedestrians results in fewer delays suffered compared to other road users, but also to increased risk exposure *(17)*. Due to differences in speed, mass and protection compared to other road users (i.e. motor vehicle occupants), pedestrians are far more vulnerable and suffer increased risk of serious or fatal injury in road crashes *(1)*.

In particular, despite the fact that pedestrian facilities (e.g. crosswalks, traffic signals) allow pedestrians to cross at designated locations, it has been shown that pedestrians make crossing decisions dynamically and often spontaneously along their trip, by accepting traffic gaps once they become available *(18)*, and on the basis of their perception of the road and traffic environment *(19)*. Moreover, crossing outside pedestrian facilities, mid-block crossing, or jaywalking are common practice among pedestrians *(20)*, aiming to minimize walking distance and delays. Consequently, the largest proportion of pedestrians road crashes in urban areas occur outside designated crossing locations *(21)*.

Microscopic analyses of pedestrians exposure have been proposed in only a few studies. For example, it has been suggested to use the number of pedestrians crossing a given road section at given time intervals *(22)*, or the product of the number of vehicles and the number of pedestrians crossing a given road section at given time intervals *(23)*. Another study *(24)* proposed a composite indicator of pedestrians exposure, taking into account pedestrian characteristics, road and traffic conditions, as well as pedestrian compliance with traffic rules. The traffic conflicts technique has also been used for measuring the exposure of pedestrians at specific crossing locations *(25)*.

Earler research *(26, 27)* proposed a microscopic indicator of pedestrians exposure in relation to vehicle speed, pedestrian walking speed and crossing width. This indicator reflects the proportion of space unavailable to pedestrians for unobstructed and safe crossing, i.e. the proportion of space which is occupied by vehicles. In recent research *(2)* an in-depth analysis was carried out on the basis of this indicator, specific limitations were identified and an improved indicator was proposed, as will be explained in detail in the following sections.

The existing approaches for estimating pedestrians road crash risk exposure are summarized in Table 1.

TABLE 1 Summary of pedestrian exposure indicators

		Scope				Macroscopic indicators					Microscopic indicators				Variables			
Source	**Year**	Risk	Exposure	Behaviour	**Field survey data**	Population	Number of trips	Walking distance	Walking time	Number of crossings	Pedestrians*Vehicles	Pedestrian characteristics*Behaviour	Traffic conflicts	Vehicles*Crossing time	Age / gender	Road type	Traffic control	Day / Night
Jonah & Engel	1983	●	●		●		●	●	●	●					●	●		●
Howarth	1982		●		●			●		●					●	●		●
Lee & Abdel-Aty	2005	●	●		●				●						●	●	●	●
Keall	1995	●	●		●		●		●	●					●		●	
Baltes	1998	●	●		●			●							●			●
Routledge et al.	1974		●											●				
Cameron	1982		●		●						●					●	●	
Van der Molen	1981		●	●								●			●	●		
Garder	1989	●	●										●				●	
Lassarre et al.	2007		●	●										●				

It is deduced that macroscopic indicators may be appropriate for an overall assessment of pedestrians exposure and the calculation of aggregate risk indicators. However, these aggregate indicators cannot be applied for isolated locations or individual pedestrians. Most importantly, the interaction between pedestrians and vehicles is not taken into account. On the other hand, microscopic indicators allow for more accurate estimation of individual pedestrians' exposure at specific locations. However, the degree to which pedestrians crossing behavior may affect pedestrians risk exposure has not been adequately examined in existing research.

More specifically, pedestrian crossing behavior is an important determinant of pedestrians risk exposure, as a relatively unsafe crossing choice, or an unexpected or undesirable event during a vehicle / pedestrian interaction may substantially increase pedestrian risk exposure. Despite the fact that various models of pedestrian walking and crossing behavior have been presented, either on the basis of the gap acceptance theory *(28, 29, 30)*, or on the basis of pedestrians level of service *(31, 32)*, or on the basis of utility theory *(20, 33, 34, 35)*, these have not been adequately exploited for estimation of pedestrians risk exposure while road crossing.

Within this framework, the objective of the present research is the analysis of pedestrians risk exposure along urban trips in relation to crossing behavior. First, an appropriate microscopic indicator of pedestrian exposure while road crossing is selected. Second, a model of pedestrian crossing behavior is presented, together with a method for the estimation of pedestrians' exposure along a trip in relation to crossing behavior. The added value of the proposed approach is demonstrated on the basis of a pilot implementation.

METHODOLOGICAL CONSIDERATIONS

Microscopic Indicator of Pedestrian Exposure for Crossing at Isolated Locations

In the present research, an appropriate pedestrians' exposure indicator is selected, namely the Routledge indicator *(26)*, as improved in recent research *(2)*, which will be refered to as the 'adapted Routledge indicator'. More specifically, recent research *(2)* demonstrated that the adapted Routledge indicator allows the assessment of pedestrians exposure while road crossing in isolated locations with different road and traffic characteristics, and can be further combined with pedestrian crossing behavior information at the examined locations.

The original Routledge indicator provides an estimate of pedestrian exposure while crossing a single road lane at a mid-block unsignalized location, in relation to vehicle length and speed, pedestrian speed and crossing width as follows:

$$R = \frac{l + vt_c}{d} \qquad (1)$$

Where R_c is the risk exposure of road crossing, l is the mean length of vehicles, v is the mean traffic speed, t_c is the mean pedestrian speed and d is the mean vehicle headspace. As mentioned above, this indicator expresses the proportion of space unavailable to pedestrians for crossing, i.e. the proportion of space occupied by vehicles. This proportion is the ratio of the space occupied by vehicles, which is equal to the vehicle length, plus the distance covered by the vehicle during the pedestrian crossing movement, to the total space available between moving vehicles. It is noted that, according to the original indicator, an increase in traffic volume leads to a reduction of the amount of space available for crossing *(2)*.

The adapted Routledge indicator was obtained as a result of a transformation of equation (1) on the basis of the following fundamental traffic flow relationships:

$$v = v_f\left(1 - \frac{k}{k_j}\right) \quad \text{and} \quad q = kv$$

with q the traffic volume, v the traffic speed, k the traffic density, v_f is the free flow speed and k_j the traffic density at congestion conditions, while also taking into account that headspace d at congestion can be taken equal to vehicle length l, so that $k=1/d$ και $k_j=1/l$. As a result, in *(2)* the original Routledge indicator was rewritten as follows:

$$R = \frac{k}{k_j} + t_c q$$

Consequently, pedestrians exposure is proportional to traffic speed and density, with R=0 at free flow conditions (given that q=0 and k=0) and R>1 at high densities and towards congestion (see Figure 1). More specifically, values of the original indicator higher than 1, which are attained rather quickly in the original indicator, correspond to conditions of increased traffic density, where the spaces occupied by moving vehicles overlap, and no space is available for pedestrians. However, in a critical assessment *(2)* of the original indicator, it is noted that increased traffic density results in decreased vehicle speed and consequently crossing opportunities, although limited, may still exist. It is further discussed that the indicator comprises a static part, expressed by the ratio of the two densities, and a dynamic part, expressed by the number of vehicles encountered during the crossing. In order to address this shortcoming of the original indicator, it is suggested to delete the static part of the indicator, resulting in an adapted indicator:

$$R = t_c q \tag{2}$$

As shown in Figure 1, the adapted indicator implies that pedestrians are equally exposed to road crash risk while crossing at low traffic volumes and thus increased speed, and while crossing at high traffic volumes and thus reduced speed (v_f cprresponds to the free flow speed). The adapted indicator expresses exposure as the number of vehicles encountered by a pedestrian during crossing at a given location.

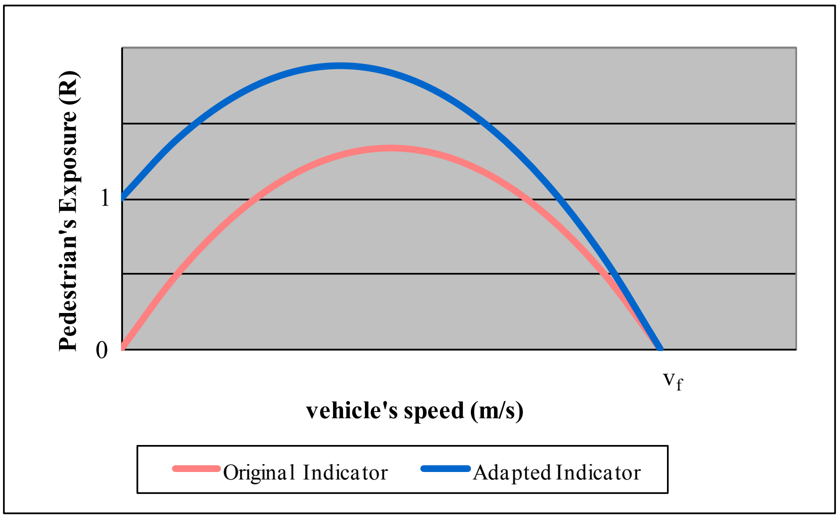

FIGURE 1 Original and Adapted Routledge Indicator (adapted from Lassarre et al. 2007)

The adapted indicator concerns crossing a single traffic lane at an isolated uncontrolled location, but can be also used in case of crossing at multiple lanes, two-way roads, separated roads etc. In general, the total exposure is estimated by integrating the exposures of each one of the lanes crossed, while taking into account that the exposure of crossing a farside lane may be increased compared to the exposure of crossing a nearside lane. For separated roads, a separate crossing movement is considered for each direction. Moreover, with a few additional adjustments, the adapted indicator can be used for estimating exposure while crossing at crosswalks (i.e. vehicle speed is adjusted to account for driver yielding behaviour), traffic signal controlled locations (i.e. the exposure is estimated only for the pedestrian phase), with or without turning vehicles (i.e. the exposure is similar to that of an uncontrolled location), as described in detail in *(2)*. Consequently, the selected indicator may be applied for the estimation of pedestrians risk exposure while crossing at any isolated location. However, for the estimation of pedestrians exposure along an entire trip, where several crossings may take place, with different alternative locations for each crossing, parameters related to the crossing choices of pedestrians need to be taken into account.

Modelling Pedestrian Crossing Behaviour along Entire Trips

For the development of models of pedestrian crossing behavior along entire trips, three issues need to be addressed *(15)*: first, a method for estimating the number of crossings that will be carried out; second, a method for the identification and definition of the potential crossing alternatives that will be examined for each crossing (i.e. the pedestrian choice set associated with each crossing decision); and third, the implementation of appropriate modeling techniques for estimating the probability to cross at each alternative location.

In recent research *(2, 3, 36)*, methods have been presented and applied for addressing these issues. A detailed presentation of these methods is beyond the scope of the present paper, and only a summary of main principles and techniques is provided, followed by a presentation of the best-performing model of pedestrian crossing behavior along a trip.

For the parameterisation of pedestrians' road crossing behaviour along a trip, a topological consideration of the urban road network and of pedestrian trips was opted for, leading to the identification of the expected number of crossings for each trip topology *(3)*. Moreover, it was proved that the location of certain crossing movements along a pedestrian trip is stochastic (primary crossings), whereas the locations of other crossing movements are deterministic (secondary crossings), and consequently the analysis of pedestrians crossing behavior may focus on primary crossings only *(2)*. It was also shown that certain trip topologies correspond to odd number of primary crossings, whereas other trip topologies correspond to even number of primary crossings *(3)*. The choice set for each primary crossing can also be identified.

An indicative example of the proposed theory for determining the number of crossings along a trip, their type (i.e. primary or secondary) and their related choice sets is presented in Figure 2. More specifically, the topology of the road network is described by a graph with links and nodes, and the origin and the destination of a pedestrian trip are located on the graph neighborhood; in this case, three alternative pedestrian trips may be considered: (a), (b) and (c) (left panel of Figure 2). In trip (a), only secondary roads - that are represented by a dotted line - are crossed. On the contrary, in trip (b) the primary graph - represented by a continuous line - is crossed on the first and second road link, followed by a crossing of a secondary road. In the third alternative trip (c), the first link of the primary graph is crossed at another location, then the secondary road is crossed from the other side of the primary graph compared to path (b), and then the third link of the primary graph is crossed (middle panel of Figure 2).

From this example, it can be understood that crossing locations of secondary roads of the graph are deterministic, because they depend on the locations of the primary crossings of the trip graph. If trip (a) is opted for, three crossings at deterministic locations are expected; these are classified as secondary crossings. However, if either trip (b) or (c) is opted for, then two crossings of the graph at stochastic locations are expected (i.e. one crossing somewhere along the first link, and one crossing somewhere along either the second or the third link); these are classified as primary crossings. In both trips (b) and (c), a crossing of the secondary road between links 2 and 3 will be made; this is classified as secondary crossing, since its location (i.e. on which side of the graph this will take place) can be fully determined once the location of the second primary crossing is determined. Therefore, each primary crossing is associated with a set of alternative locations, with a crossing probability $P<1$ for each location (stochastic choice). On the other hand, once the primary crossing choice probabilities are determined, it is possible to determine the location of the secondary crossings, i.e. the secondary crossing probability $P=1$ in the respective locations (deterministic choice).

The choice sets of the two primary crossings for trips (b) and (c) are presented in the right panel of Figure 2, where the parts of the primary graph that correspond to each choice set (e.g. one primary crossing somewhere along the first link, and another primary crossing somewhere along the second or the third link) are highlighted with blue bars. The length of each bar corresponds to the length of the choice set (number of road links) and their direction suggests the direction of the crossing movement that will take place within this choice set.

A generalization of the above principles was carried out for various pedestrian trip topologies *(36)*, resulting in an algorithm for determining the choice set of each primary crossing along any pedestrian trip. The crossing choice set of each primary crossing comprises a number of consecutive road links traveled by pedestrians, and each road link may include two alternative crossing locations, one at junction and one at mid-block.

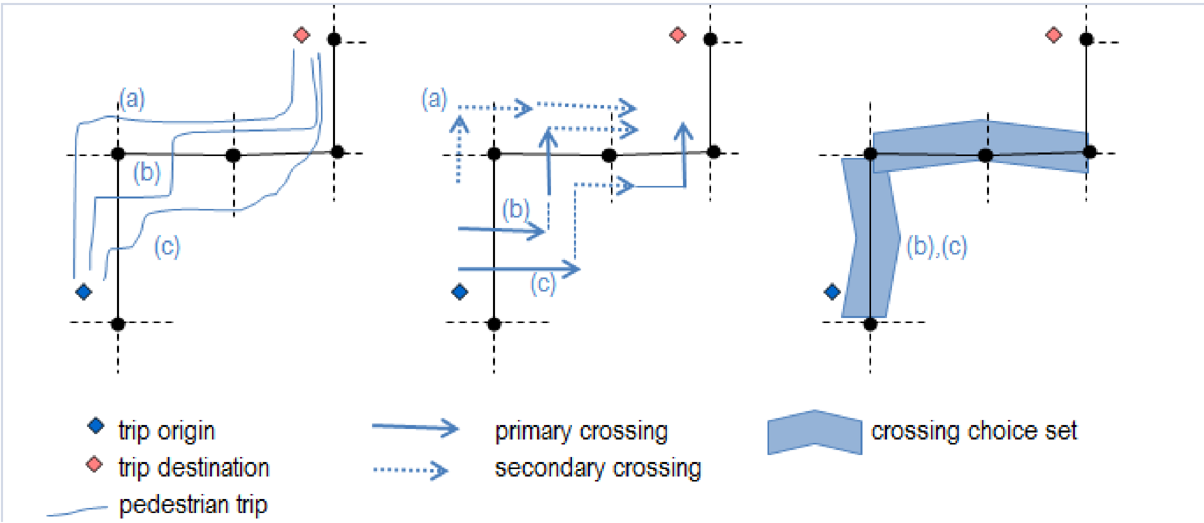

FIGURE 2 Left panel: Origin, destination and topology of a pedestrian trip - Middle panel: primary and secondary crossings - Right panel: primary crossing choice sets

The choice of primary crossing location among the available alternatives can be then modelled by means of discrete choice models *(37, 38, 39)*. Different hypotheses have been examined as regards the pedestrians' decision making process, namely a sequential choice process and a hierarchical choice process *(3)*. The hierarchical process of modeling the location of each primary crossing along pedestrian trips is based on the assumption that the pedestrian considers the entire set hierarchically, by first selecting a road link among the available alternatives (marginal choice), and then a specific location, either at junction or at mid-block within that link (conditional choice). In this case, multinomial nested or cross-nested logit models may be applied. An alternative assumption would be that a pedestrian examines the available choice set sequentially, by making a separate crossing decision on each link of the choice set. In this case, sequential multinomial or nested logit models may be examined.

Recent research *(3)* implemented the above theory, on the basis of data from a field survey, in which pedestrian trips in urban areas were recorded in real time using a video camera. Survey participants were selected with simple random sampling from the exits of metro stations in Athens, Greece. In total, 491 pedestrian trips were recorded, including 2.418 road segments (links) - including both one-way and bidirectional roads - and 884 primary road crossings. For each trip a total of 52 variables were collected, concerning characteristics of the pedestrians (age, gender, speed etc.), the trips (length, duration, origin, destination etc.), the road links (number of directions, number of lanes, sidewalk width, roadside parking, traffic volume, traffic signals etc.) and the road crossings (location, type etc.).

From the comparative assessment of various models developed, it was found that that a sequential decision making process hypothesis is more appropriate for modeling crossing choices of pedestrians along a trip, being a less restrictive assumption (e.g. no prior knowledge of the road network is assumed) and resulting in better fitting models *(3)*. A sequential logit model was developed for each road link, with three alternatives, namely crossing at mid-block (0), crossing at junction (1) and not crossing (2) (see Figure 3).

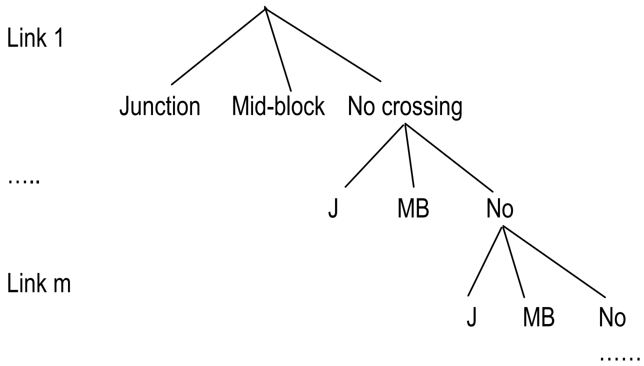

FIGURE 3 Structure of the sequential logit model of pedestrian crossing behaviour

Individual-specific heterogeneity was tested, given that sequential choices of a group of 279 individuals were in fact modeled, but was not found to be significant. Moreover, state dependence was included in the utility functions of the alternatives by means of appropriate control variables, expressing the sequence of decisions along the road links of the choice set.

The best fitting sequential logit model, estimated by means of the BIOGEME dedicated software for discrete choice models *(40)* is presented in Table 2. The parameter estimates can be interpreted as follows:

- the alternative-specific constants suggest that overall not crossing a road link is more likely than crossing, which seems intuitive given that each choice set includes several road links, out of which only one is chosen.
- A change of trip direction (defined as a change of street by means of a turning movement) increases the probability of crossing at junction (B_changedir).
- There is an increased probability of crossing at the first road link of each choice set (B_first). Moreover, having skipped one or two crossing opportunities increases the utility of crossing (B_skip1, B_skip2).
- An increase of the percentage of the trip length increased the utility of crossing both at junction and at mid-block (B_plength).
- the utility of crossing decreases with the logarithm of pedestrian walking speed (B_vped), revealing a tendency of faster pedestrians to postpone road crossing.
- Traffic signals increase the utility of crossing at junction (B_signal).
- Low traffic volume increases the utility of crossing at mid-block (B_trafficL).
- The presence of two lanes (B_lanes2) reduces the probability of crossing at junction compared to the presence of one lane. It is noted that, in the examined dataset, two lane roads generally correspond to moderate road and traffic conditions and it is not surprising that mid-block crossing is common in these conditions.

The modeling results suggest that road and traffic conditions, as well as trip characteristics, may have important impact on the probability that each alternative location along a pedestrian trip is chosen for crossing. It is noted that several road and traffic characteristics were found to be highly correlated in the study areas; for instance, the presence of sidewalks was associated with higher traffic volumes and larger roads, whereas roadside parking was associated with low traffic volumes and smaller roads. Consequently, some of the road and traffic variables included in the final model also reflect other features of the road and traffic environment.

TABLE 2 Parameter estimates and fit of the sequential model of pedestrian crossing behavior

Utility functions

0 - Cross at Mid-block	Constant_0 + B_first * first + B_skip1 * skip1 + B_skip2 * skip2 + B0_changedir * L_changedir + B_vped2 * I_logvped2 + B0_trafficL * L_trafficL + B0_trafficH * L_trafficH + B_plength * L_plength
1 - Cross at Junction	Constant_1 + B_first * first + B_skip1 * skip1 + B_skip2 * skip2 + B_vped2 * I_logvped2 + B1_signal * J_signal + B1_lanes1 * L_lanes1 + B1_lanes2 * L_lanes2 + B1_lanes3 * L_lanes3 + B_plength * L_plength
2 - No Crossing	Constant_2

Utility parameters

Name	Description	Value	Robust Std err	Robust t-test	p-value
Constant_0		-0.14	1.59	-0.09	0.93
Constant_1		-0.183	1.630	-0.110	0.910
Constant_2		0.000	.	.	.
B0_changedir	A change of trip direction occurs at the end of this road link	-0.526	0.263	-2.000	0.050
B0_trafficH	High traffic volume	0.000	.	.	.
B0_trafficL	Low traffic volume	0.441	0.210	2.100	0.040
B1_lanes1	One lane	0.000	.	.	.
B1_lanes2	Two lanes	-0.633	0.275	-2.310	0.020
B1_lanes3	Three or more lanes	0.331	0.286	1.160	0.250
B1_signal	Traffic signal at junction	0.641	0.234	2.740	0.010
B_first	First road link	0.614	0.343	1.790	0.070
B_plength	Percentage of the total trip length	1.660	0.368	4.520	0.000
B_skip1	Pedestrian did not cross at the previous road link	0.769	0.366	2.100	0.040
B_skip2	Pedestrian did not cross at the two previous road links	0.061	0.495	0.120	0.900
B_vped2	The logarithm of pedestrian speed	-0.569	0.370	-1.540	0.120

Model: Multinomial Logit
Number of estimated parameters: 12
Number of observations: 680
Null log-likelihood: -699.617
Final log-likelihood: -591.514
Likelihood ratio test: 216.207

Pedestrians' Exposure in Relation to Crossing Behaviour

The adapted Routledge indicator allows to estimate pedestrian risk exposure (R_i) for crossing a road at an isolated location in relation to road geometry, traffic control and traffic conditions. By definition, the risk exposure implied by the adapted Routledge indicator is independent from the crossing probability, which is taken equal to 1. However, the sequential logit model developed allows one to estimate the probability (P_i) of crossing at each location within the pedestrians choice sets along a trip. Consequently, it is possible to estimate the exposure at each location along a pedestrian trip in relation to the crossing probability.

More specifically, a different definition of pedestrian exposure while road crossing can be formulated. When a crossing location is examined within a pedestrian trip, it may be included in one of the choice sets of the primary crossings that will be carried out along the trip, and therefore a crossing probability lower than one corresponds to that location. In this case, the actual pedestrians exposure (R') for the examined location within the specific trip will be lower than the theoretical one (R), which is estimated on the basis of the adapted Routledge indicator. Therefore, for each location (i) along a pedestrian trip:

$$R_i' = P_i * R \qquad (3)$$

Consequently, for the entire trip, the total risk exposure of pedestrians may be estimated as the weighted mean of the exposure at all the (n) alternative crossing locations along a trip in relation to the related crossing probabilities, as follows:

$$R' = \sum_{i=1}^{n} P_i * R_i \qquad (4)$$

IMPLEMENTATION

Characteristics of the study area

The proposed methodology is demonstrated within an application for a typical trip in the centre of Athens, Greece, for four scenarios including different traffic conditions and different types of pedestrians. In particular, a pedestrian trip from the ‘Evangelismos’ metro station to the Kolonaki square in the centre of Athens, via the Marasli st. and the P.Ioakeim st. is considered. The study area and the examined trip are shown in Figure 4.

The trip graph includes 3 road links on Marasli st. separated by 2 perpendicular roads, and 4 road links on P.Ioakeim st. separated by 3 perpendicular roads. Given the topology of the trip and the origin / destination locations, and by applying the related algorithm (36), two primary crossings are expected, one along Marasli st. and one along P.Ioakeim st. The choice set of the 1st primary crossing includes all 3 road links of Marasli st. and the choice set of the 2nd primary crossing includes all 4 links along P.Ioakeim st. Moreover, 2 secondary crossings of the perpendicular roads are expected along Marasli st., and 3 secondary crossings of the perpendicular roads are expected along P. Ioakeim st. In an alternative trip path, pedestrians might not cross the two primary roads at all and reach their destination while only making secondary crossings; however, since this case does not involve a probabilistic crossing choice (all secondary crossing have crossing probability equal to one), it is not examined in the present application.

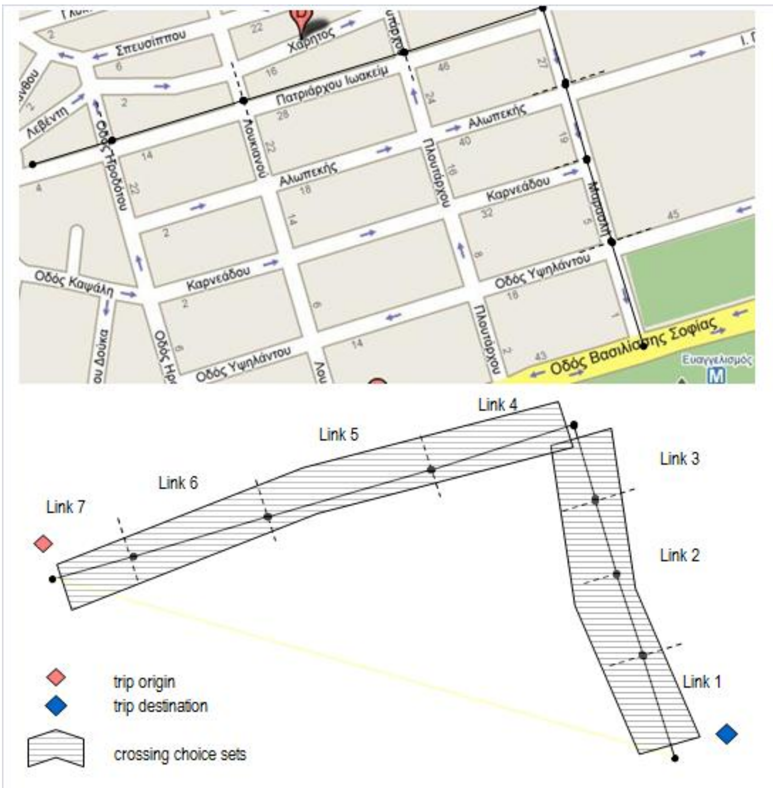

FIGURE 4 Map of the study area and characteristics of the pedestrian trip examined

Moreover, Table 3 summarises the geometric and traffic characteristics of the road network of the examined trip, which will be used in the calculation of exposure and crossing probabilities. The cumulative trip length is calculated for each road link. Moreover, the 1st road link of Marasli st. includes an exclusive ambulance lane, while at the 2nd and 3rd link of Marasli st. the related road width is used for roadside parking. A change of trip direction is assigned at the end of the 3rd link. Finally, two values of hourly traffic volume are considered in each case, one for peak conditions (high traffic volume) and one for off-peak conditions (low traffic volume).

TABLE 3 Road geometry and traffic characteristics along the pedestrian trip examined

Street		Cumulative trip length	% of trip length	Traffic signal	Number of lanes	Change of direction	Lane width	Low traffic volume (veh/h/lane)	High traffic volume (veh/h/lane)
Marasli	Link 1	115	0.151	Yes	2	No	2.75	250	500
	Link 2	235	0.309	No	1	No	2.75	250	500
	Link 3	297	0.391	No	1	Yes	2.75	250	500
P.Ioakeim	Link 4	420	0.553	Yes	2	No	3.00	500	1000
	Link 5	548	0.721	Yes	2	No	3.00	500	1000
	Link 6	663	0.872	No	2	No	3.00	500	1000
	Link 7	760	1.000	Yes	2	No	3.00	500	1000
Secondary roads	Links 1-2			No	1		2.75	100	200
	Links 2-3			No	1		2.75	100	200
	Links 4-5			Yes	2		2.75	150	300
	Links 5-6			No	2		2.75	150	300
	Links 6-7			Yes	1		2.75	250	500

Estimation of pedestrian exposure regardless of crossing behaviour

On the basis of the geometric and traffic characteristics of the road network, the exposure (R) of each alternative crossing location along the trip was estimated by means of the adapted Routledge indicator, regardless of the related crossing probability. As mentioned above, on each road link, two crossing alternatives are considered, one at junction and one at mid-block. This exposure is the product of the traffic volume and the pedestrian crossing time in seconds, which is taken as the ratio of the lane width to the walking speed of pedestrians. Two values of walking speed were considered, on the basis of the data collected during the field survey for the development of the crossing behaviour model: a low value equal to the mean walking speed minus its standard deviation, which was found to be 0.82 m/s, and a high value equal to the mean walking speed plus its standard deviation, which was found to be 1.50 m/s. The crossing of a second, farside lane is indicatively considered to be twice the exposure of crossing the first, nearside lane. Moreover, a 20% probability of traffic signal violation from the pedestrian was considered, as shown by the field survey data.

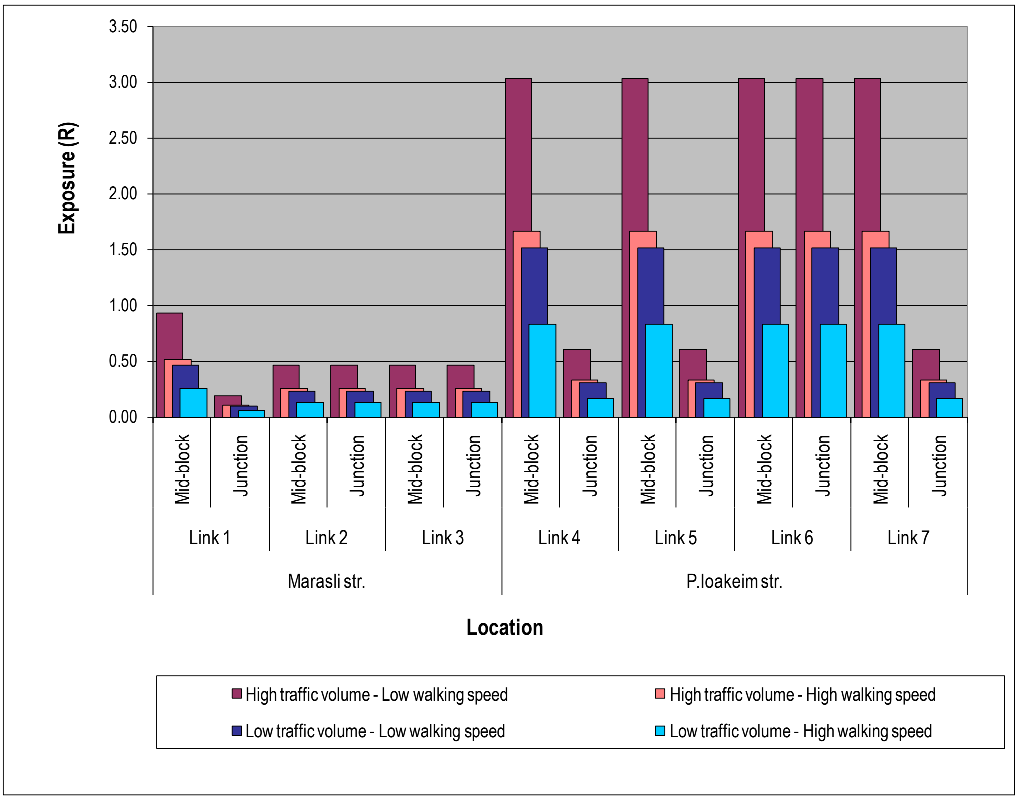

FIGURE 5 Exposure (*R*) at each location along the trip, regardless of the crossing probability (*P*)

The results presented in Figure 5 reveal increased exposure at the locations of P.Ioakeim st., due to the increased number of lanes and the increased traffic, both at peak and off-peak conditions, and reduced exposure at signal-controlled locations. Concerning the four examined scenarios, the exposure at each location increases for low walking speed and high traffic volume, which is intuitive. The highest exposure at each location corresponds to the 'low walking speed - high traffic volume' scenario.

It is also interesting to note that the exposure at each location is not significantly different between 'high traffic volume - high walking speed' and 'low traffic volume - low walking speed', which suggests that faster pedestrians may partly compensate for the increased exposure suffered in high traffic volumes, so that it becomes similar to the exposure that slower pedestrians suffer at lower traffic volumes.

Estimation of crossing probabilities along a pedestrian trip

The sequential logit model presented in Table 2 was applied for each one of the choice sets of the two primary crossings for the four scenarios examined. The distribution of crossing probabilities along the examined trip is presented in Figure 6, where the two separate curves correspond to the two separate choice sets with ΣP_i=1 for each choice set.

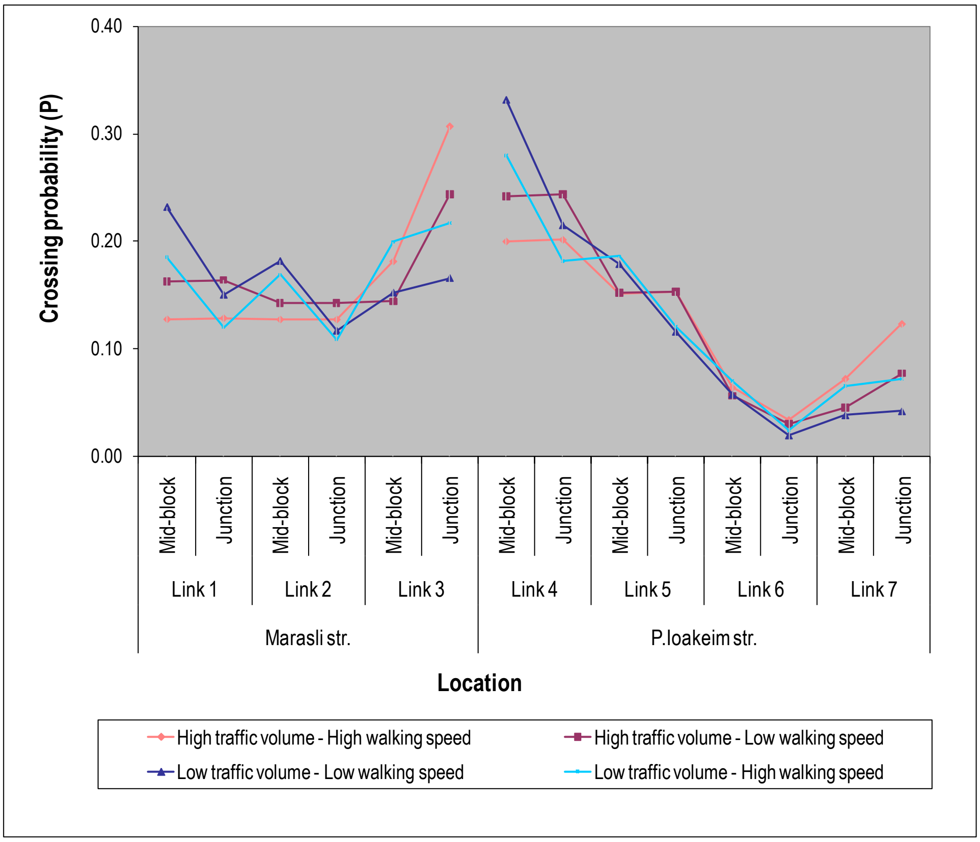

FIGURE 6 Distribution of crossing probabilities (*P*) along the trip

Increased crossing probabilities are observed at the beginning, and partly towards the end of each choice set at increased traffic volumes. There appear to be a tendency of pedestrians - especially of faster ones - to postpone road crossing. This trend is less pronounced along the P.Ioakeim st., where the road and traffic environment is somewhat more complex. It is also observed that crossing at mid-block is more likely than crossing at junction when the traffic volume is low on Marasli st. Moreover, crossing probability at junction is slightly higher at high traffic volume on P.Ioakeim st. There is a tendency of slower pedestrians to cross at signal-controlled locations.

Overall, a pattern may be observed, according to which the first primary crossing takes place at the end of the first choice set and the second primary crossing takes place at the beginning of the second choice set, so the two crossings are clustered nearby the Marasli - P.Ioakeim junction.

These results confirm the important effect of traffic volume, walking speed and traffic control on crossing behaviour along a trip.

Estimation of pedestrian exposure along a trip in relation to crossing behaviour

The final step of the analysis concerns the estimation of exposure (*R'*) for each location along the trip. As regards primary crossings, the above crossing probabilities are used, whereas for secondary crossings, the crossing probabilities are taken equal to one. The results are presented in Figure 7, where additional columns are presented for the secondary crossings along the trip. These results show that specific locations with increased pedestrian risk exposure are identified within the trip. Pedestrians risk exposure increases with traffic volume and decreases with pedestrian speed. It is also observed that pedestrians with increased walking speed may partly compensate for their risk exposure, so that it is not significantly affected by traffic volume.

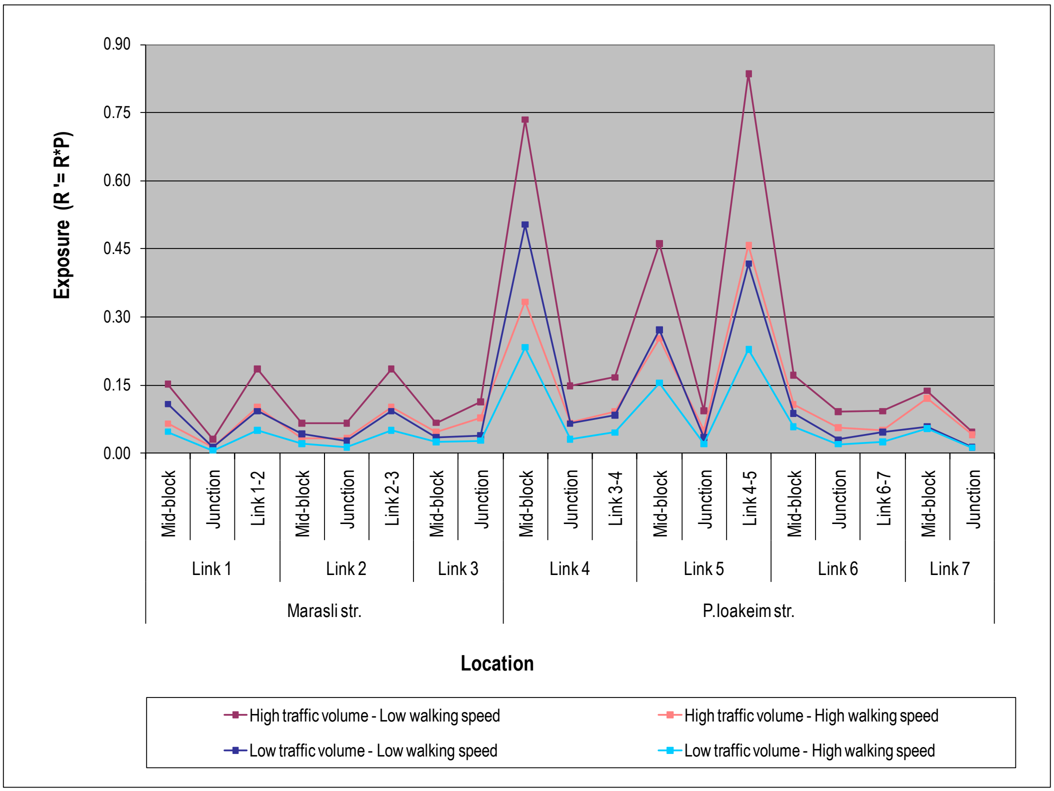

FIGURE 7 Exposure (*R'*) along the trip in relation to crossing probability (*P*)

In all four scenarios, increased exposure is observed at the Marasli-P.Ioakeim junction (i.e. Link 3- Link 4), where the change of trip direction occurs, and therefore there is increased likelihood of combining the two primary crossings in that junction area.

Pedestrians with low walking speed are most exposed, primarily because of the increased time of their interaction with vehicles, and to a lesser extent due to their crossing choices. It is also noted that slower pedestrians are more sensitive to the increased exposure of mid-block locations, although they do not demonstrate increased probability of mid-block crossing, especially at high traffic volumes. On the contrary, faster pedestrians present less variation in their exposure between junction and mid-block locations.

Finally, it can be noticed that pedestrians' exposure during secondary crossings is generally low, although these crossings are assigned a choice probability equal to one. An exception concerns the secondary crossing between Links 4 and 5; this crossing corresponds to the only non-signalised junction along the busy P.Ioakeim st. It is thereby underlined that the classification of some crossings as 'secondary' does not imply a lower importance of these crossings in terms of pedestrians' exposure; it simply means that no probabilistic choice is involved as regards the location of these crossings, and the related risk exposure is directly estimated on the basis of the adapted Routledge indicator. On the other hand, a number of alternative locations are available for each primary crossing, and consequently the related risk exposure needs to be estimated in relation to the choice probability of each alternative location.

A final note concerns the analysis of secondary crossings at t-junctions; in this case, depending on the trip path, the secondary road may or may not be crossed. The probability to cross the secondary road could be in this case taken as the cumulative probability of primary crossing until the point where the secondary road is to be crossed (i.e. the secondary crossing occurs only if the primary crossing behaviour of the pedestrian leads him to the arm of the t-junction that corresponds to a secondary road). For practical reasons, this specific case has not been examined in the present example.

DISCUSSION

The results of the case study presented above suggest that, although the shape of the distribution of pedestrians' risk exposure along a trip may be similar in different scenarios, the magnitude of the changes in risk exposure from changes in the examined parameters may be important. In Figure 4, for example, the exposure for crossing link 4 at mid-block is 4 times higher in the ‘worst case’ scenario (high traffic / low pedestrian speed) than in the ‘best case’ scenario (low traffic / high pedestrian speed). Moreover, specific locations with increased pedestrian risk exposure can be identified for each pedestrian trip, and this increased exposure can be interpreted on the basis of a combination of roadway, traffic and behavioural parameters.

On the basis of the above, a notion of ‘variable risk exposure’ of each location of the road network is outlined. More specifically, although a location of the road network is theoretically associated with a given risk exposure, regardless of the crossing probability at this location, the actual risk exposure of a pedestrian at this location within a specific trip is different from (i.e. lower than or equal to) the theoretical one, on the basis of the crossing probability at this location.

Consequently, for the accurate estimation of the risk exposure corresponding to a location of the road network, it is necessary to estimate the crossing probability at this location. It is interesting to note, however, that the exposure of pedestrians at a specific location of an urban road network with the same traffic conditions will be different in different trips, because there is a different probability of selecting this location for crossing in different trips.

In terms of road safety in numbers, the proposed approach could be applied in the assessment of road crash risk, either at isolated locations or at an area-wide level. First, pedestrian origin-destination and pedestrian volume information for all alternative paths would be required. The crossing behaviour model would provide the crossing probabilities along each path, allowing to estimated the pedestrian risk exposure for each location of each path, for a given pedestrian volume.

The following implication can be thus identified: the calculation of the total pedestrians exposure for a specific location of the road network, , requires the analysis of all pedestrian trips travelled through this specific location in an area-wide level (i.e. the calculation of the exposure on the basis of crossing behaviour for all related trips). Eventually, crash risk rates may be calculated by dividing the number of crashes recorded at each location to the amount of exposure at each location.

CONCLUSIONS

The present research addressed a number of conceptual and methodological issues involved in the analysis of pedestrians risk exposure in urban areas, focusing on the further refinement of microscopic exposure indicators, their adjustment from local level to trip level, and the use of crossing behaviour data at trip level. Existing research results were exploited and further developed, leading to an appropriate framework for analysis of pedestrians' exposure along urban trips in relation to their crossing choices. The implementation of the proposed approach for different scenarios revealed several aspects of pedestrians' behaviour and exposure.

An appropriate microscopic exposure indicator was selected and further improved. A sequential logit model was developed for the estimation of crossing probabilities for each alternative location along a pedestrian trip. A process is also presented for estimating pedestrian risk exposure on the basis of crossing behaviour. The whole approach is generic and can be applied for the analysis of any pedestrian trip in urban areas. The results of the present research also reveal a group of crucial parameters, which are common in the description of both pedestrians crossing behaviour and pedestrians exposure while road crossing, namely the road width, the traffic volume, the walking speed and the traffic signals.

The proposed microscopic approach is proved to be more advantageous compared to standard macroscopic approaches, in which exposure indicators such as the time or distance travelled, the number of crossings of the traffic volume along the trip are used. In the proposed approach, a much finer distribution of pedestrian exposure along the trip is obtained, explicitly taking into account the important variations in road geometry and traffic conditions that may be encountered along the trip. As explained above, the proposed approach may, under certain conditions, be applied for estimating the risk exposure of a pedestrian population i.e. on an area-wide level.

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