

ANALYSIS OF PEDESTRIAN RISK EXPOSURE IN RELATION TO CROSSING BEHAVIOUR

Eleonora Papadimitriou, PhD (Corresponding author)
Research Associate
National Technical University of Athens
Department of Transportation Planning and Engineering
5 Heroon Polytechniou st., GR-15773 Athens
Tel: +302107721380, Fax: +302107721454
E-mail: nopapadi@central.ntua.gr

George Yannis
Associate Professor
National Technical University of Athens
Department of Transportation Planning and Engineering
5 Heroon Polytechniou st., GR-15773 Athens
Tel: +302107721326, Fax: +302107721454
E-mail: geyannis@central.ntua.gr

John Golias
Professor
National Technical University of Athens
Department of Transportation Planning and Engineering
5 Heroon Polytechniou st., GR-15773 Athens
Tel: +302107721276, Fax: +302107721454
E-mail: igolias@central.ntua.gr

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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.

1 BACKGROUND AND OBJECTIVES

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

13 Pedestrians road crash risk is most often examined within the framework of
14 macroscopic pedestrian safety analyses (4). The lack of information on pedestrians risk
15 exposure is one of the main limitations of macroscopic road safety analyses internationally
16 (5, 6). The road crash risk of pedestrians is mainly estimated on the basis of macroscopic
17 indicators, such as the number of road crashes or casualties to the population of pedestrians
18 (7, 8), the walking distance travelled (9), the walking time spent (10), the number of trips (11)
19 or the number of road crossings (12, 13).

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

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

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

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

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

53

54 **TABLE 1 Summary of pedestrian exposure indicators**

55

Source	Year	Scope			Field survey data	Macroscopic indicators				Microscopic indicators				Variables			
		Risk	Exposure	Behaviour		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
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		•	•									•				

56

57

58

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

67 More specifically, pedestrian crossing behavior is an important determinant of
 68 pedestrians risk exposure, as a relatively unsafe crossing choice, or an unexpected or
 69 undesirable event during a vehicle / pedestrian interaction may substantially increase
 70 pedestrian risk exposure. Despite the fact that various models of pedestrian walking and
 71 crossing behavior have been presented, either on the basis of the gap acceptance theory (28,
 72 29, 30), or on the basis of pedestrians level of service (31, 32), or on the basis of utility theory
 73 (20, 33, 34, 35), these have not been adequately exploited for estimation of pedestrians risk
 74 exposure while road crossing.

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

81

82

83 **METHODOLOGICAL CONSIDERATIONS**

84

85 **Microscopic Indicator of Pedestrian Exposure for Crossing at Isolated Locations**

86

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

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

96

$$97 \quad R = \frac{l + vt_c}{d} \quad (1)$$

98

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

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

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

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

115

$$116 \quad R = \frac{k}{k_j} + t_c q$$

117

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

128 to address this shortcoming of the original indicator, it is suggested to delete the static part of
 129 the indicator, resulting in an adapted indicator:

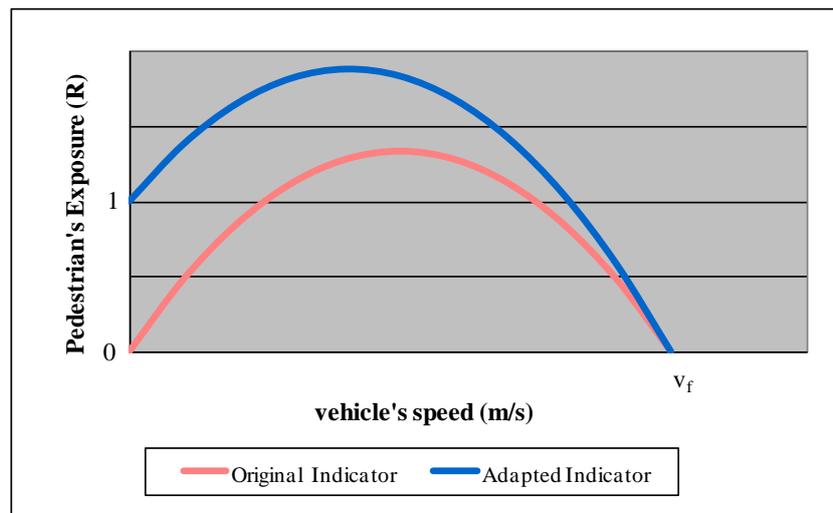
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$$131 \quad R = t_c q \quad (2)$$

132

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

138



139

140

141 **FIGURE 1 Original and Adapted Routledge Indicator (adapted from Lassarre et al.**
 142 **2007)**

143

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

159

160 **Modelling Pedestrian Crossing Behaviour along Entire Trips**

161

162 For the development of models of pedestrian crossing behavior along entire trips, three issues
 163 need to be addressed (15): first, a method for estimating the number of crossings that will be
 164 carried out; second, a method for the identification and definition of the potential crossing

165 alternatives that will be examined for each crossing (i.e. the pedestrian choice set associated
166 with each crossing decision); and third, the implementation of appropriate modeling
167 techniques for estimating the probability to cross at each alternative location.

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

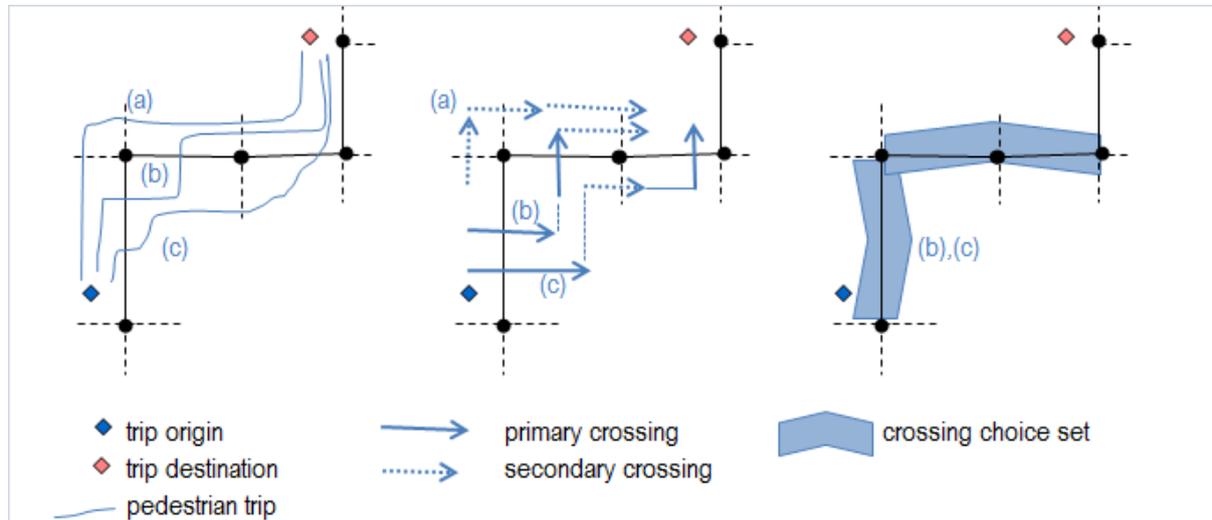
172 For the parameterisation of pedestrians' road crossing behaviour along a trip, a
173 topological consideration of the urban road network and of pedestrian trips was opted for,
174 leading to the identification of the expected number of crossings for each trip topology (3).
175 Moreover, it was proved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

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

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

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

214 A generalization of the above principles was carried out for various pedestrian trip
 215 topologies (36), resulting in an algorithm for determining the choice set of each primary
 216 crossing along any pedestrian trip. The crossing choice set of each primary crossing
 217 comprises a number of consecutive road links traveled by pedestrians, and each road link
 218 may include two alternative crossing locations, one at junction and one at mid-block.
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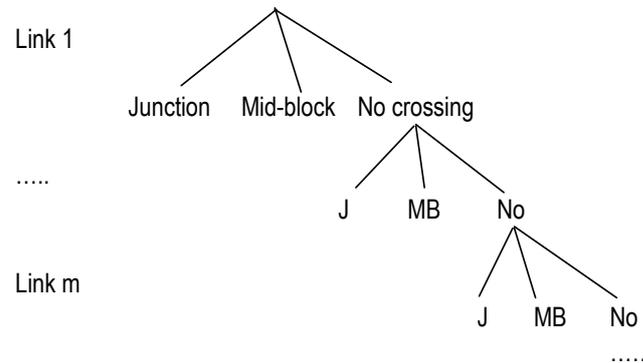
223 **FIGURE 2 Left panel: Origin, destination and topology of a pedestrian trip - Middle**
 224 **panel: primary and secondary crossings - Right panel: primary crossing choice sets**
 225

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

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

247 From the comparative assessment of various models developed, it was found that that
 248 a sequential decision making process hypothesis is more appropriate for modeling crossing
 249 choices of pedestrians along a trip, being a less restrictive assumption (e.g. no prior
 250 knowledge of the road network is assumed) and resulting in better fitting models (3). A

251 sequential logit model was developed for each road link, with three alternatives, namely
 252 crossing at mid-block (0), crossing at junction (1) and not crossing (2) (see Figure 3).
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 255

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

257

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

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

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

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

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294**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

295 Model: Multinomial Logit
296 Number of estimated parameters: 12
297 Number of observations: 680
298 Null log-likelihood: -699.617
299 Final log-likelihood: -591.514
300 Likelihood ratio test: 216.207
301**302 Pedestrians' Exposure in Relation to Crossing Behaviour**

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304 The adapted Routledge indicator allows to estimate pedestrian risk exposure (R_i) for crossing
305 a road at an isolated location in relation to road geometry, traffic control and traffic
306 conditions. By definition, the risk exposure implied by the adapted Routledge indicator is
307 independent from the crossing probability, which is taken equal to 1. However, the sequential
308 logit model developed allows one to estimate the probability (P_i) of crossing at each location

309 within the pedestrians choice sets along a trip. Consequently, it is possible to estimate the
 310 exposure at each location along a pedestrian trip in relation to the crossing probability.

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

$$318 \quad R'_i = P_i * R \quad (3)$$

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

$$324 \quad R' = \sum_{i=1}^n P_i * R_i \quad (4)$$

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328 **IMPLEMENTATION**

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330 **Characteristics of the study area**

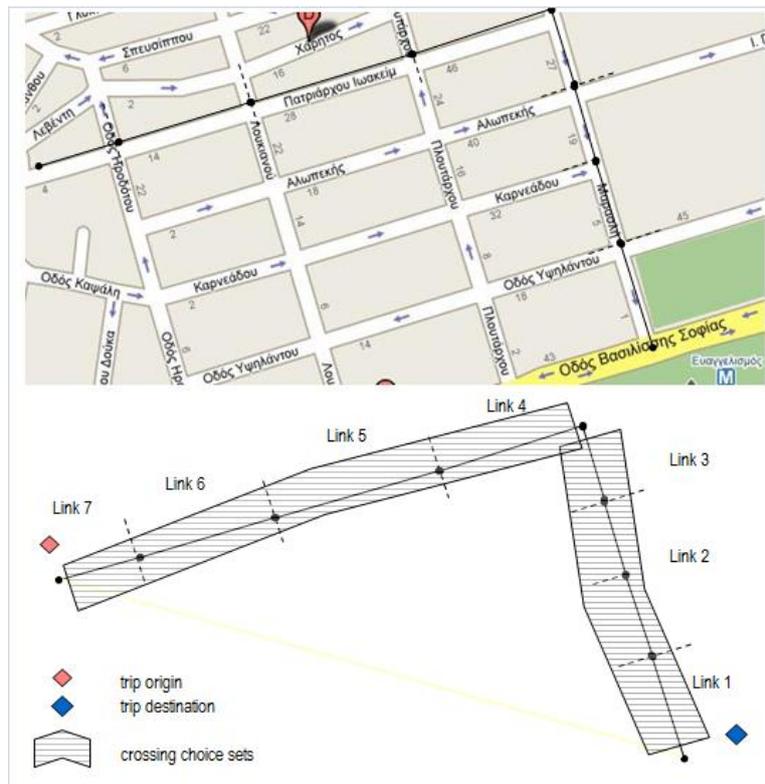
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332 The proposed methodology is demonstrated within an application for a typical trip in the
 333 centre of Athens, Greece, for four scenarios including different traffic conditions and
 334 different types of pedestrians. In particular, a pedestrian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

337 The trip graph includes 3 road links on Marasli st. separated by 2 perpendicular roads,
 338 and 4 road links on P.Ioakeim st. separated by 3 perpendicular roads. Given the topology of
 339 the trip and the origin / destination locations, and by applying the related algorithm (36), two
 340 primary crossings are expected, one along Marasli st. and one along P.Ioakeim st. The choice
 341 set of the 1st primary crossing includes all 3 road links of Marasli st. and the choice set of the
 342 2nd primary crossing includes all 4 links along P.Ioakeim st. Moreover, 2 secondary crossings
 343 of the perpendicular roads are expected along Marasli st., and 3 secondary crossings of the
 344 perpendicular roads are expected along P. Ioakeim st. In an alternative trip path, pedestrians
 345 might not cross the two primary roads at all and reach their destination while only making
 346 secondary crossings; however, since this case does not involve a probabilistic crossing choice
 347 (all secondary crossing have crossing probability equal to one), it is not examined in the
 348 present application.

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

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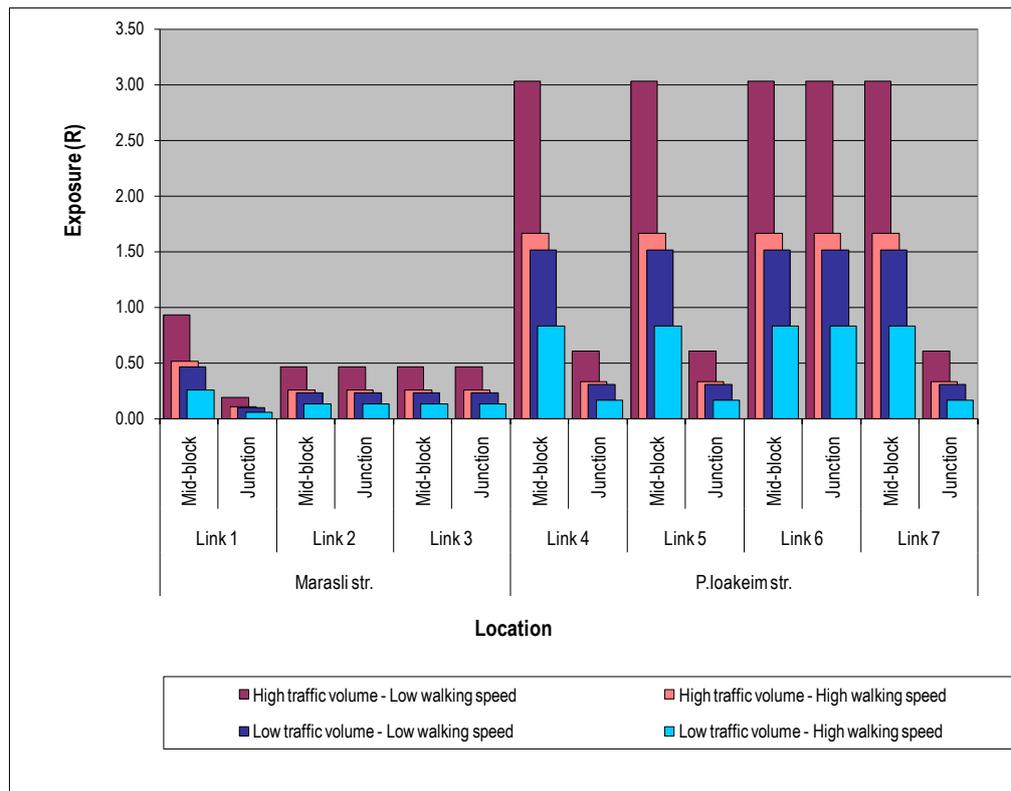
Moreover, Table 3 summarises the geometric and traffic characteristics of the road network of the examined trip, which will be used in the calculation of exposure and crossing probabilities. The cumulative trip length is calculated for each road link. Moreover, the 1st road link of Marasli st. includes 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).

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367**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

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369370
371**Estimation of pedestrian exposure regardless of crossing behaviour**

372 On the basis of the geometric and traffic characteristics of the road network, the exposure (R)
373 of each alternative crossing location along the trip was estimated by means of the adapted
374 Routledge indicator, regardless of the related crossing probability. As mentioned above, on
375 each road link, two crossing alternatives are considered, one at junction and one at mid-block.
376 This exposure is the product of the traffic volume and the pedestrian crossing time in
377 seconds, which is taken as the ratio of the lane width to the walking speed of pedestrians.
378 Two values of walking speed were considered, on the basis of the data collected during the
379 field survey for the development of the crossing behaviour model: a low value equal to the
380 mean walking speed minus its standard deviation, which was found to be 0.82 m/s, and a high
381 value equal to the mean walking speed plus its standard deviation, which was found to be
382 1.50 m/s. The crossing of a second, farside lane is indicatively considered to be twice the
383 exposure of crossing the first, nearside lane. Moreover, a 20% probability of traffic signal
384 violation from the pedestrian was considered, as shown by the field survey data.
385



386
387

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

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390

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

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

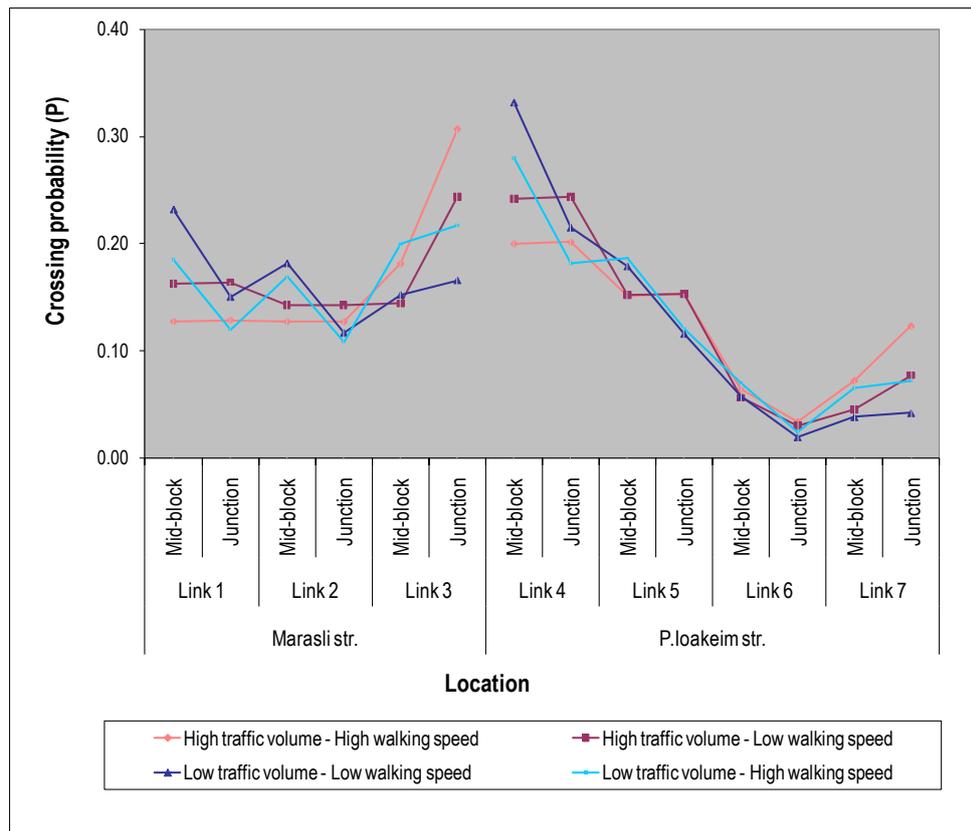
402
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Estimation of crossing probabilities along a pedestrian trip

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405

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

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

415

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

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

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

430

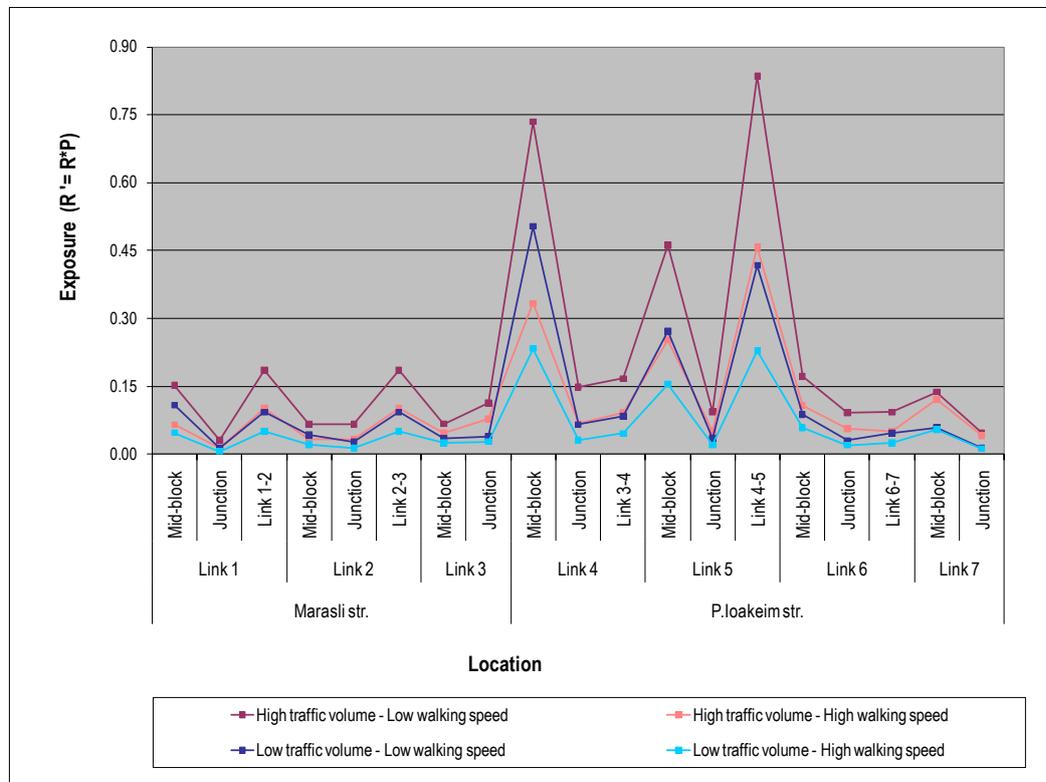
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432 Estimation of pedestrian exposure along a trip in relation to crossing behaviour

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434 The final step of the analysis concerns the estimation of exposure (R') for each location along
435 the trip. As regards primary crossings, the above crossing probabilities are used, whereas for
436 secondary crossings, the crossing probabilities are taken equal to one. The results are
437 presented in Figure 7, where additional columns are presented for the secondary crossings
438 along the trip. These results show that specific locations with increased pedestrian risk
439 exposure are identified within the trip. Pedestrians risk exposure increases with traffic

440 volume and decreases with pedestrian speed. It is also observed that pedestrians with
 441 increased walking speed may partly compensate for their risk exposure, so that it is not
 442 significantly affected by traffic volume.
 443
 444



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 446

447 **FIGURE 7 Exposure (R') along the trip in relation to crossing probability (P)**
 448

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

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

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

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

476

477

478 **DISCUSSION**

479

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

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

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

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

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

513

514

515 **CONCLUSIONS**

516

517 The present research addressed a number of conceptual and methodological issues involved
518 in the analysis of pedestrians risk exposure in urban areas, focusing on the further refinement

519 of microscopic exposure indicators, their adjustment from local level to trip level, and the use
 520 of crossing behaviour data at trip level. Existing research results were exploited and further
 521 developed, leading to an appropriate framework for analysis of pedestrians' exposure along
 522 urban trips in relation to their crossing choices. The implementation of the proposed approach
 523 for different scenarios revealed several aspects of pedestrians' behaviour and exposure.

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

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

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