Measuring accident risk exposure for pedestrians in different micro-environments

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Abstract

Pedestrians are mainly exposed to the risk of road accident when crossing a road in urban areas. Traditionally in the road safety field, the risk of accident for pedestrian is estimated as a rate of accident involvement per unit of time spent on the road network. The objective of this research is to develop an approach of accident risk based on the concept of risk exposure used in environmental epidemiology, such as in the case of exposure to pollutants. This type of indicator would be useful for comparing the effects of urban transportation policy scenarios on pedestrian safety. The first step is to create an indicator of pedestrians' exposure, which is based on motorised vehicles' “concentration” by lane and also takes account of traffic speed and time spent to cross. This is applied to two specific micro-environments: junctions and mid-block locations. A model of pedestrians' crossing behaviour along a trip is then developed, based on a hierarchical choice between junctions and mid-block locations and taking account of origin and destination, traffic characteristics and pedestrian facilities. Finally, a complete framework is produced for modelling pedestrians' exposure in the light of their crossing behaviour. The feasibility of this approach is demonstrated on an artificial network and a first set of results is obtained from the validation of the models in observational studies.

Key-words: pedestrian; accident; exposure; micro-environment; crossing behaviour.

1. Introduction

Measuring accident risk exposure for pedestrians is not an easy task. Usually researchers use estimates of the time spent or the distance walked on the road network during a pedestrian trip, on the basis of data collected by means of household surveys, questionnaires or field observations e.g. following pedestrians along a road (Julien, Carré, 2002). In most cases, however, little or no information is available on the conditions of the trip e.g. whether it is on a busy road or not, whether the crossings are made at junctions or mid-block locations, on or outside a marked crosswalk, and so on. Due to this lack of information about the micro-environments met by pedestrians, only global (macroscopic) risk indicators can be measured, and these indicators are heavily dependent on the often poor quality of accident data for pedestrians. In order to better assess pedestrians risk exposure, information has to be collected about the crossings made during the trip and the related conditions. In exposure science and environmental epidemiology, it is a common practise to collect detailed and precise data about the quality of the micro-environments in which an individual stays or moves (Guerin et al., 2003). This type of approach is used in the present research to develop a methodology for assessing the risk exposure of pedestrians in urban areas.

1.1. Main pedestrian accident scenarios

There are various circumstances in which a pedestrian can be hit by a moving vehicle. These circumstances can be analysed in terms of the actions taken by the pedestrian and / or the vehicle and their relative setting on the road network. For instance, an encounter or interaction with a moving vehicle may occur when a pedestrian is either standing or walking on the pavement or in the road, when crossing the road, and so on. Moreover, the incidence of accidents in which pedestrians are involved while crossing the road occur in different proportions between 'junctions' and 'mid-block locations', according to the structure of the road network. Hence, the relative numbers of accidents between locations with and without pedestrian facilities depends on the local transport policy and the resources devoted to pedestrian safety. The consequences of an accident, measured by the injury severity, are a function of the impact speed, the vehicle design, the road design and the vulnerability of the pedestrian.

In the following analysis, it is assumed that pedestrians are at risk only when crossing a road. This assumption is quite realistic, as non-crossing accidents generally represent a small proportion of pedestrian accidents (Duncan et al. 2002). The characteristics taken into consideration include those relating to the traffic (traffic volume and speed), the road design (road width, median, marked crosswalks) and the traffic signals (colour lights and pedestrian crossing signs). No distinction is made between different types of vehicles.

Nevertheless, these restrictions leave space for complexity, especially when considering the possibilities rising from different types of behaviour at crossings. For a pedestrian trip from a given origin to a given destination, there may be different routes, each one entailing different sequences of crossing options of different types, which in turn correspond to different micro-environments. The choice between these sequences of options is a trade-off between the pedestrian's perception of risk, his willingness to take his time in reaching his destination and his desire to feel comfortable, and these parameters may vary according to the characteristics of the individual.

1.2. What is exposure?

In this research, the definition of accident exposure when crossing roads is analogous to exposure air pollution when walking in urban areas. In environmental epidemiology, the National Academy of Science (1991) defines exposure as “an event that occurs when there is a contact at the boundary between a human and the environment with a contaminant of a specific concentration for an interval of time”. On the road network, a direct (physical) contact occurs only in case of an accident, that is to say, a collision between a road user and a vehicle that generates mechanical energy, which is the cause of the damage, during a certain amount of time. D. Briggs (2000) gave some reasons why “a looser definition of exposure may often need to be applied when health is considered in the sense of positive well-being, rather than merely ill-health”.. Moreover, there is a virtual contact between a road user and an “atmosphere” generated by the traffic. The quality of the “atmosphere” depends on the presence of “contaminants” that correspond, in the traffic, to the moving vehicles and are described by a traffic volume and a speed. The difficulty is to define an appropriate “concentration” suited to the situation of road crossing. The time of exposure can be defined by the time spent by the pedestrian for crossing a road of a certain width with a walking speed. The time spent in traffic has always been a recommended indicator of what road safety specialists call a measurement of “risk exposure”. Moreover, the walking speed of a pedestrian depends on his or her age , the trip purpose, and so on.

2. Exposure assessment

2.1. Selection of an exposure indicator

We start from a measure of accident risk proposed by Routledge and al. (1974a, b, 1976):

$$P_c = \frac{L + vt_c}{d}$$

Where:

P_c: the accident risk of the crossing
ℓ : the average length of the vehicle
v: the average speed of the flow
t_c : the average crossing time for a pedestrian
d: the average traffic gap,

as shown in Figure 1.

Figure 1 to be inserted here

This indicator is meant to yield the proportion of space that is not available to the pedestrian for crossing the road freely and safely (i.e. that is occupied by a virtual flow of vehicles). The space is equal to the length of the vehicle plus the distance travelled by the vehicle during the time taken by the pedestrian to cross the road. It is also a measure of accessibility to the other side of the road. If there are long vehicles, travelling quickly and in large numbers, one cannot access the other side of the road because one faces a kind of “moving wall” and if one chooses to cross, one has an increased accident risk. However, there are some weaknesses in this indicator, which are analyzed and assessed in the following paragraphs.

In particular, from the traffic theory, there exists a monotonic decreasing function between speed (v) and density (k), measured in number of vehicles per kilometre. For a linear function, we have:

$$v = v_f\,(1 - \frac{k}{k_J})$$

with (v_f) the free speed when the flow tends to zero, (k_J) the “jam” density in saturation conditions. As (d) is equal to the gap between the front of the following vehicle to the rear of the preceding one plus the length of the vehicle, we have the relations:

$$k = \frac{1}{d} \quad \text{and} \quad k_J = \frac{1}{\ell}$$

because in case of jam the gap becomes null and (d) is equal to the length (ℓ) of the vehicle.

Then the Routledge indicator becomes:

$$
\begin{aligned}
P &= k(\frac{1}{k_J} + t_c v) \\
&= k_J(1-\frac{v}{v_f})(\frac{1}{k_J} + t_c v) = (1-\frac{v}{v_f})(1+t_c k_J v)
\end{aligned}
$$

This risk indicator is proportional to the density of vehicles and to the speed of the flow. In saturation conditions, v = 0 and P = 1. If there is no traffic, v = v_f , P = 0. There is a maximum greater than one at $v = \frac{v_f}{2} - \frac{1}{2k_J t_c}$ (Figure 2).

However, (P) is not a proportion as asserted erroneously by Routledge et al. (1974a, b), because the virtual vehicle lengths can overlap and in this case (P) is greater than 1. (P) can be interpreted as the average number of virtual vehicles in one unit of length, which one can meet when crossing the road. In the formula, there is a static and a dynamic part. The first is expressed by the ratio of two densities and the second is expressed by the number of vehicles that pass during the time the pedestrian crosses:

$$
\begin{aligned}
P &= k(\frac{1}{k_J} + t_c v) \\
&= (\frac{k}{k_J} + t_c kv) = (\frac{k}{k_J} + t_c q)
\end{aligned}
$$

with (q) the traffic volume (measured in number of vehicles per hour) q=kv according to the fundamental relationship of traffic theory.

As explained above, when (P) is higher than 1, the flow of vehicles is a “wall”, which a pedestrian cannot cross. However, as the traffic is nearly saturated and the speed is low, opportunities to cross between vehicles may still exist.

As it stands, the Routledge indicator has some drawbacks, therefore. The value P= 1, signifying that it is quite impossible to cross, is attained quite quickly when traffic density increases. Furthermore, when the traffic is nearly saturated and the speed very low, the value is still 1 because of the impossibility of crossing, although the risk is also low and the indicator should be less than 1. The lack of accessibility may be high in dense traffic conditions, but the accident risk is relatively low.

To avoid this drawback, we propose to suppress the constant term related to the saturation density in the equation, which becomes a symmetric parabola, as shown in Figure 2:

$$P = k\,t_c v = (1 - \frac{v}{v_f}) t_c k_J v = t_c q$$

Figure 2 to be inserted here

The “concentration” of vehicles expressed by the modified indicator is now just equal to the average number of vehicles that pass during the time taken to cross. The magnitude of the modified indicator is smaller, however. For instance, in the symmetric indicator, the “concentration” would be equal both at speed v=5m/s and v=15m/s, while for the initial asymmetric indicator the “concentration” would be higher at speed v=5m/s than for v=15m/s, because of the density of the traffic. The symmetry assumption could be tested by means of field observations and/or a roadside experiment, or by a computer or traffic simulator experiment.

2.2. Exposure at junctions and mid-block locations, protected or unprotected

The proposed exposure assessment algorithm is based on the identification of traffic flows through which a pedestrian crosses; each moment of pedestrian risk exposure consists of crossing a one-lane traffic flow, qualified by a “concentration” (e.g. exposure) indicator (C) for a duration (t) equal to the time taken to cross and a width (L) equal to the crossing distance. The time taken to cross is equal to the width of the lane divided by the walking speed v_c (=1,4 m/s).

2.2.1. Mid-block locations

For each road crossed at mid-block, we consider number of flows to be crossed, (m), as shown in Figure 3. We suppose that for two-way roads, the flows are distinct: one in each direction. If there are more lanes in each direction, we create more distinct flows in each direction from the aggregated two-way flow. Therefore, for a one-way road there is at least one flow to cross, for a two-way road at least two flows, and so on. The flow in one direction is then broken down into distinct flows by lane. If two flows are physically separated (e.g. by a median), two independent crossings are considered (one from each direction) instead of a global one. Moreover, a marked crosswalk, offering protection at mid-block crossings, may be available and needs to be considered. A vehicle-pedestrian interaction can also be considered at marked crosswalks, by imposing a speed reduction on the vehicle flow (e.g. by 20%). It is noted that this is example is just a suggestion; further measurements are necessary to assess the level of alertness of the drivers in vehicle-pedestrian interactions.

More specifically, where there is no separation, we calculate the (m) “concentrations”:

$C_i = q_i\, v_c\, (L_1 + L_2 \ldots + L_i)$,

and the time:

$T_i = L_i / v_c$

and the speed v_i , and note the presence or not of a marked crosswalk. Where there is a separation, we calculate (m_1) exposures:

$C_{1i}= q_{1i}\, v_c\, (L_{11}+ L_{12} ...+L_{1i})$

and (m_2) exposures:

$C_{2i}= q_{2i}\, v_c\, (L_{21}+ L_{22} ...+L_{2i})$,

and the times

$T_{1i} = L_{1i}/v_c$ and $T_{2i} = L_{2i}/v_c$

and speeds and note the presence or not of a marked crosswalk.

There are two special points to note. When leaving the pavement, the exposure for crossing a far-side lane is higher than the exposure for crossing a near-side lane. In case of the same traffic volume on each lane, the exposure on the far-side lane is expected to be exactly twice the exposure on the near-side lane (i.e. 2qvL versus qvL). For that reason, we cumulate the crossing distances. One should consider carefully the order of the crossed flows from the departure roadside. Moreover, when there is a separation, the crossing distance should be reset to zero. By calculating all the individual flow exposures, we obtain a micro-environmental exposure assessment.

Figure 3 to be inserted here

2.2.2. Traffic controlled junction or mid-block locations

At junctions with traffic signals, two phases for pedestrian crossings can be considered: one when the lights are green for pedestrians (i.e. they are red for vehicles, with the possible exception of turning movements) and one when the lights are red for pedestrians (i.e. they are green for vehicles). When the lights are green for pedestrians, a pedestrian may be exposed to two types of risk: one resulting from the flow of turning vehicles (from or into adjacent roads), and another one resulting from vehicles not complying with the red light. Some turning movements can be constrained by country regulations. When the lights are red for pedestrians, a pedestrian is exposed if he chooses to disregard them and attempts to cross the road. We assume that pedestrians do not cross outside marked crosswalks at junctions.

The calculation of exposure is then as follows:

- When the lights are green for pedestrians and when non-compliant vehicles are taken into account, the exposure is calculated according to the same procedure and formulae as for mid-block locations. It is noted that this assumption has to be checked with data about red-light running violations in relation to the traffic condition.
- When the lights are green for pedestrians and vehicles turning left or right are taken into account, the flow of traffic turning in each direction is measured, aggregated and distributed proportionally to the number of lanes in that direction. Each lane of

traffic is assumed to be one-way. The speed is taken as equal to the maximum of the speeds of the turning vehicles. The exposure is then calculated as for mid-block locations.

- When the lights are red for pedestrians and non-compliant pedestrians are taken into account, the exposure is assumed to be equal to the case in which the lights are green for pedestrians and non-compliant vehicles are taken into account.

3. Crossing behaviour modelling

According to the above, accident risk exposure can be estimated for any location (micro-environment) along a pedestrian trip, where a pedestrian is likely to cross. However, in order to estimate the total exposure for an entire trip, it is necessary to model pedestrian behaviour, in terms of the choice of crossing location .

Previous research on pedestrian movement in urban areas is extensive and ranges from modelling pedestrian behaviour and vehicle-pedestrian interactions, to accident analyses and evaluation of safety measures. However, few attempts have been made to model pedestrians' crossing behaviour at the level of an individual trip. Several theories and approaches have been proposed for pedestrian modelling. Most see crossing behaviour as largely governed by the gap-acceptance theory, which states that each pedestrian has a critical gap to cross the road (Manuszac et al., 2005, Hamed, 2001). Another interesting approach for estimating crossing preferences concerns pedestrian level-of-service models (Sarkar, 1995, Baltes, 2002, Guttenplan et al., 2001). In addition, a promising approach for modelling pedestrian crossing behaviour is offered by discrete choice models, which correlate crossing decisions to a utility function (Evans, Norman, 1998, Hine, Russel, 1993).

However, an overall approach to pedestrians' crossing decisions (i.e. the places where pedestrians are most likely to cross), has not yet been presented. More specifically, most studies analyse crossing decisions at a particular location, while the behaviour of pedestrians along an entire trip has not been explored in detail. Moreover, crossing at uncontrolled locations (mid-block crossing, jaywalking etc.), which is a common pattern of behaviour, is not taken into account in most studies. Finally, most studies are not designed to link observed crossing behaviour to pedestrian risk exposure.

The pedestrian behaviour model outlined below provides a tool to estimate crossing probabilities for each location along any pedestrian trip. It is based on existing models, which were adapted for the purposes of this research, while additional tools were developed as well. The results of modelling pedestrian crossing behaviour can be combined with corresponding risk exposure estimates to calculate the total weighted exposure of a pedestrian along a trip.

3.1. Basic principles

This approach is based on several principles. First of all, the analysis aims to model “real-life” situations in an urban network, where pedestrian trips may be more or less complex and include several changes of direction. In this research, crossing behaviour along a trip with several changes of direction is considered to be similar to those along a corresponding trip with no change of direction. Road sections along a complex route are thus transformed to a single, linear, uni-directional sequence of roads. Accordingly, the origin and the destination of a trip are taken to be the beginning and end of this continuous route.

Based on the above, two categories of crossing can be considered, taking into account the network layout:

- “Primary” crossings made at junctions or mid-block locations (with change of direction) selected for the purpose of following the particular route.
- “Secondary” crossings made at junctions on either side of the road (without change of direction) while moving along sequential road links (i.e. additional crossings made as a consequence of following the route).

An example of “primary” and “secondary” crossings is presented in Figure 4a.

Figure 4a to be inserted here

The proposed model yields probabilities for primary crossings only; secondary crossings probabilities (i.e. whether these take place on the origin side or on the destination side of the trip roadway) depend on and can be calculated from the primary crossings probabilities. For example, in Figure 4, if a primary crossing takes place across the first road link, the first secondary crossing takes place on the origin side of the roadway. However, if no primary crossing takes place across the first road segment, then the first secondary crossing would take place on the destination side of the trip roadway.

From the above definition, it is obvious that the classification into “primary” and “secondary” crossings does not mean to imply that the former are more important or more difficult ones than the latter. In practice, it is perfectly possible that a secondary crossing involves crossing a major road and a primary crossing involves crossing a minor road. The specific classification is solely related to the nature of the crossings in terms of modelling approach; a “primary” crossing is probabilistic, in the sense that it can be made on various locations along the trip, whereas a “secondary” crossing is deterministic, in the sense that it can be made either on the origin or on the destination side of the roadway at a specific location along the trip.

The total number of primary crossings along a trip depends thus on the origin-destination combination in relation to the side of the roadway along the trip. In particular, if the origin and destination are on the same side of the roadway, a pedestrian would not have to cross; if the origin and destination are on different sides of the roadway, a pedestrian would have to cross. Moreover, in complex trips with several changes of direction, pedestrians are likely to make additional primary crossings, in order to minimize their walking distance.

For example, in the top part of Figure 4b, an example of a trip on which origin and destination are on the same side of the roadway is presented; a pedestrian could either walk along the origin side of the roadway (and not cross at all) or cross twice, in order to reach the destination. Moreover, the bottom part of Figure 4b shows an example of a trip on which origin and destination are on different sides of the roadway; in this case, it is shown that a pedestrian would either have to cross once, or three times, in order to reach the destination.

Figure 4b to be inserted here

On the basis of the above, the total number of crossings N along a pedestrian trip can be estimated through a distribution as follows:

- If origin-destination are on the same side of the roadway, then N {0, 2, 4, …}
- If origin-destination are on different sides of the roadway, then N {1, 3, 5, …}

3.2. Model development

3.2.1. Model for a single road link

The baseline case of one single road link (i.e. a road segment between junctions) is examined first. Assuming that the pedestrian's origin and destination are located on different sides of the road link, he or she has a choice between different crossing locations: one of the two junctions or some location at mid-block (between the two junctions). Therefore, pedestrians crossing decisions are considered to follow a two-level hierarchical structure:

Level 1: Junction or mid-block?
Level 2: If junction, which one?

In order to model this decision process, we used a nested logit model formulated by Chu et al. (2002) . In that study, a crossing scenario was presented to survey participants, who were asked to state their crossing preferences. They were given several options to choose from: two options for crossing at a junction and up to four options for crossing at a mid-block location. The nested logit model fitted to the data has thus a two-level structure. The top level has two branches: junctions (I) and mid-block locations (M). The bottom level has two options in the junction branch and up to four options in the mid-block branch (B: cross first – walk later, C: jaywalk, D: walk first – cross later, F: use mid-block crosswalk) . Explanatory variables mainly concern road characteristics.

The calculation of probabilities also follows a two-level procedure. The utility U_O for option O is defined as the sum of the products of all variables values with the corresponding coefficients.

Utility function $U_o = \Sigma$ (Variable*Coefficient)

The probability of a crossing option being chosen is the product of its marginal and conditional choice probabilities. The marginal probability represents the probability of choosing junctions or mid-block options. The conditional probability is the probability of choosing a particular crossing option once the choice has been made between junction or mid-block.

The model considered in the present research is part of this nested logit model, which is better adapted to the needs of the analysis. In particular, the top level of the model (junction or mid-block) is used to obtain Level 1 marginal crossing probabilities, and the "junction" branch of the bottom level of the model is used to obtain Level 2 conditional crossing probabilities for junction. It should be noted that the crossing options of the "mid-block" branch of the bottom level of the model are not considered, as they are not useful in this research; however, they are used to calculate the utilities and inclusive values of the top level. Moreover, option F -to use mid-block crosswalk - can be used in roads links with mid-block crosswalks as the Level 2 conditional probability for mid-block. The analysis would then have the following structure:

Level 1:	Junction or mid-block?
Level 2.1:	If junction, which one?
Level 2.2:	If at mid-block, on mid-block crosswalk or not?

It should be noted that a series of variables sensitivity tests were carried out for the final model, allowing for minimizing the number of variables. The crossing behaviour model considered for single road links is presented in Table 1.

Table 1 to be inserted here

3.2.2. Model for a pedestrian trip

If we consider a pedestrian trip along a sequence of, for example, three road links between six traffic controlled junctions, the resulting crossing probabilities produced by the crossing behaviour model would have the general form shown in Figure 5: crossing probabilities are significantly higher at junctions than in mid-block locations. We thus obtain a uniform probability distribution along the trip is obtained, as all links along a pedestrian trip are considered to be equivalent, in the sense that no preference for a particular link (or section) is taken into account.

Figure 5 to be inserted here

However, it is necessary to account for the different weights that different links or sections may have in the crossing preferences of a pedestrian. This parameter related not so much to the traffic and geometry parameters of the road that make it more likely to be chosen than another, as to the natural tendency of an individual to to behave in a particular way along a given route.

In order to incorporate this parameter in the model, some functions of the nested logit model are used (Chu et al, 2002). In particular, the mid-block branch options of the nested logit model were not exploited so far, but were simply used to obtain the total marginal probability for mid-block. As mentioned above, these options are:

- B: cross first and walk later
- C: cross diagonally (jaywalk)
- D: walk first and cross later
- F: use a mid-block crosswalk

Options B, C, D can be considered to express an individual's tendency to cross earlier or later (or randomly select a section) along a link. Three utility functions correspond to these options. If these three functions are isolated from the rest of the model, one can notice the following; when the walking distance is different for the three options, different utility combinations are obtained. However, when the walking distance is the same for the three options, the same utility distribution is obtained, regardless of the value of the walking distance.

Therefore, considering a trip of a given length, along a number of links, and that all other variables are equal along the trip, , one can calculate the following probabilities on the basis of the respective utility functions:

B: cross first and walk later	$P= 0.579$
C: cross diagonally (jaywalk)	$P= 0.064$
D: walk first and cross later	$P= 0.358$

One can thus consider that the probability B describes the tendency to cross at the beginning of the trip, the probability D describes the tendency to cross towards the end of the trip and the probability C describes the tendency to cross in the middle of the trip. By attributing these probability values to the starting point (0% of the distance), the ending point (100% of the distance) and the middle of the trip (50% of the distance) respectively, one can obtain a non-uniform probability distribution, as shown in Figure 6.

Figure 6 to be inserted here

In the equation, the value x corresponds to the percentage of the total length of the trip. The equation is generic and may be applied to any pedestrian trip, in order to weight each link in terms of its location along the route.

The final crossing probabilities for each option along a pedestrian trip are calculated by weighting the uniform crossing probabilities (junction or mid-block for each road link) with the non-uniform crossing probability distribution (crossing earlier or later along the trip). The general form of the resulting final crossing probability distribution along the trip is presented in Figure 7. Figure 7, also as Figure 5, refers to the case of a pedestrian trip along three road links. Moreover, the estimated probabilities in Figure 7 are obtained by weighting the estimated probabilities of Figure 5 with the non-uniform probability distribution. While in Figure 5 the interim locations are identified according to their type (e.g. junction or mid-block) and the link on which they are located (i.e. link 1, link 2 or link 3), in Figure 7 the same locations are identified according to their distance from the trip origin, as a percentage of the total length of the trip.

Figure 7 to be inserted here

It should be also noted that the model ultimately yields independent crossing probabilities i.e. these do not add up to one. This is in accordance with our initial assumption that, in any pedestrian trip, there may be additional crossings (over and beyond the minimum required). However, in the event that only one crossing is to be considered, the final probabilities can be rescaled to add up to one, and can thus be considered to be dependent.

3.3. Summary and validation

A hierarchical methodology is used to estimate pedestrians' crossing behaviour, consisting of the following steps:

1. Estimation of the total number of crossings along a trip, in relation to origin and destination parameters.
2. Estimation of crossing probabilities at different locations along each road segment (link).
3. Estimation of crossing probabilities along the trip, in relation to the distance from origin and destination.
4. Calculation of the weighted final crossing probabilities for each location along the trip.

On the basis of the above, a model for estimating the type, number and location of crossings along a trip was developed. The resulting algorithm makes it possible to calculate probabilities for different pedestrian crossing choices along a trip through a limited yet sufficient number of variables.

Preliminary validation of the model yielded promising results. However, there is some evidence that there is room for improvement, mainly as regards a more precise calibration of the parameters.

In particular, the first step of the model, entailing the selection of the total number of crossings, was validated on the basis of real data from a pedestrian survey in Lille, France (WHO, 2006, Lassarre et al, 2005). It was confirmed that, if trip origin-destination are on the same side of the roadway, then the total number of crossings N follows distribution N {0, 2, 4, …}. It also suggested that further calibration is necessary for the particular case of trips along a single direction (e.g. N=0). Moreover, it was confirmed that, if trip origin-destination are on different sides of the roadway, then the total number N of crossings follows a distribution N {1, 3, 5, …}.

As far as step 2 of the model is concerned, the transformation of the nested logit model proved to be sufficient for describing the distribution of crossing probabilities along a road link (junction or mid-block). Validation was based on two data sets (WHO, 2006):

- CCTV recordings of crossing decisions of 1,870 pedestrians in Florence, Italy, on a road link between two uncontrolled junctions
- A field survey in Athens, Greece, recording crossing decisions of 1,793 pedestrians on a road link between two traffic controlled junctions.

The results showed non-significant differences among model predictions and observed behaviour. It should be noted, however, that the performance of the model is improved for links with traffic controlled junctions.

Finally, the non-uniform probability distribution of the third step of the pedestrian behaviour model was compared with real data from the Lille pedestrian survey. The basic assumptions of the model were found to be accurate (higher probability of crossing at the beginning or the end of the trip). There again, however, there is room for improvement after calibration for different area types, given certain particularities of the survey area in Lille (i.e. an area around the university campus where there are only few traffic controlled junctions).

The above results adequately validate the proposed model. It is noted that the model includes an important number of explanatory variables, whose combination can capture the majority of conditions encountered in urban areas. Within this framework, the survey sites on which data was collected were representative of different urban conditions. Consequently, the proposed model can be applied to the majority of urban settings. Further calibration, in order to account for special or local conditions might be required and would certainly be interesting. The incorporation of interactions between pedestrians is also an interesting field for further improvement of the model.

4. Feasibility demonstration

4.1. An example

Figure 8.1 shows three pedestrian routes in the Quartier Latin district of Paris. In addition, Figure 8.2 shows the main pedestrian traffic control facilities (traffic signals, marked crosswalks).

Figure 8.1-2 to be inserted here

We will look only at the crossings along the main network, where there is no separation of flows. According to the methodology presented above, these trips can be considered along a single direction, by taking into account the network layout (which affects the number of secondary crossings), as shown in Figure 9.

Figure 9 to be inserted here

For each trip, the pedestrian crossing model is applied as described above, in order to obtain primary crossings probabilities. In Table 2, for instance, the uniform crossing probability distribution - i.e. the crossing probabilities (junction 1, junction 2 or mid-block) - are calculated for each road link of the trip. Then, the non-uniform probability distribution is estimated in relation to the distance of each crossing option from the trip origin. The final crossing probabilities are obtained as the product of the uniform and non-uniform probability distributions. These final (independent) probabilities can also be rescaled to add up to one, in the event that they are considered to be dependent.

Table 2 to be inserted here

Figure 10 shows the final scaled (dependent) probability distributions for each trip:

Figure 10 to be inserted here

Furthermore, for each one of the primary crossing options of each trip, a measure of accident risk exposure can be obtained as in Table 3. For each junction or mid-block location, the information required related to three flows: one in each direction, plus one turning movement in case of a junction. Additionally, the exposures for each of the secondary crossings along each trip are calculated as shown in Table 4.

Table 3 to be inserted here

Table 4 to be inserted here

Summarizing, a pedestrian's risk exposure can be weighted in relation to the different crossing options encountered along a trip and to the behaviour of pedestrians when it comes to crossing decisions. These crossing decisions mainly concern “primary” crossings, i.e. crossings that are necessary for the pedestrian in order to reach his or her destination. Moreover, on the basis of these primary crossing decisions, one can estimate the risk exposure corresponding to the “secondary” crossings, i.e. the crossings that are a consequence of following the particular route. As a result, degrees of exposure for different micro-environments can be combined with detailed information about the presence of pedestrians in these micro-environments to enable an integrated exposure assessment to be carried out..

4.2. Discussion

The feasibility of the proposed approach can be better perceived by examining the results for trip C in more detail (see Figure 10). In this trip, the origin and destination are on different sides of the roadway and therefore an odd number of crossings would be expected. Assuming that only one primary crossing will be made, an intuitive approach would be to cross around the beginning or towards the end of the trip i.e. junction 2 of link 1 or junction 1 of link 3. Indeed, the model yields increased probabilities for these particular options, thus reflecting the most reasonable strategy to be pursued in this case. It should also be noted that it is highly unlikely for this single primary crossing to be made in the middle of link 2, as link 2 should then be crossed againas a secondary crossing, and this is also reflected in the estimated probability distribution.

Assuming now that three primary crossings are made on trip C, this would actually correspond to an attempt to minimise the distance walked and follow the shortest path between the origin and the destination. In this case, it would be reasonable to consider that one crossing would be made on each of the three links. The first crossing would most likely be made at the second (traffic controlled) junction of link 1 and the last crossing would most likely be made at the first (traffic controlled) junction of link 3, while the second crossing could be made either at junction 1 at junction 2 of link 2. The mid-block option of link 2 is very unlikely to be selected, as the crossing distance is greater along this section and the traffic is denser. Hence, it would only be selected in the event of a large gap in the flow of traffic.

We thus find that the estimated probability distribution corresponds to intuitive behaviour, whatever the number of crossings considered.

A similar conclusion can be drawn from the analysis of trip A (Figure 10), which would require an even number of primary crossings. In the case of two primary crossings, the shortest intuitive path would include one crossing at the end of link 1 (junction 2 of link 1 or junction 1 of link 2) and one crossing when approaching the destination. This trend is fully reflected in the estimated probability distribution, which also indicates an increased probability of selecting a second crossing at junction 2 of the last link, which would represent a slight deviation from the shortest path for the purpose of crossing at a traffic controlled junction. These results are in accordance with general walking practice.

That said, one particular aspect of these modelling results deserves further discussion, and that is mid-block crossing, especially those made in the middle of the trip, which appear to be penalized to some extent. This may partly be due to the fact that the examples analyzed are located in an area of increased traffic. Another more obvious reason is the form of the non-uniform distribution, which further discourages the mid-block crossings of the middle of the trip. Further validation of this distribution will make it possible to calibrate the existing form and improve it if necessary.

5. Conclusion

The methodology described above yields estimated probabilities for specific crossing decisions made by pedestrians and links these decisions to their accident risk exposure. From the assumptions of the analysis and the models' structure, it is obvious that the dynamics of pedestrian decisions can be modelled within an appropriate framework. The application of the pedestrian behaviour model to three paths in the Quartier Latin district of Paris gives some promising results, which correspond to a realistic representation of pedestrian movements in accordance with the initial assumptions of the analysis. The model integrates variables related only to traffic conditions and the protection offered to the pedestrian for crossing: traffic lights or crosswalks.

An assessment of the exposures for each crossing is made on the basis of the usual information available about traffic in an urban network: traffic volumes, densities and speeds by lane and by turning movements. Lane crossing exposure, defined as a micro-environmental “concentration” of vehicles, is simply the product of the time taken to cross, which could depend on the characteristics of the pedestrian, and traffic volume, which could be on an hourly or daily basis. For one trip or a set of trips, it is possible to come up with a distribution of the exposures by combining these values with the probabilities of crossings and then estimating an average exposure value.

A microscopic simulation framework is under development, which will have the following structure. As inputs, we would have trips (which may be solely walk or by a mono or bi-mode plus a walk) and corresponding origin-destination pairs. These data could be defined by specific addresses or be randomly selected within zones. Using simulation, we would describe the route followed by the pedestrian during the trip, as a sequence of road links that he or she has to go along. The number of crossings per trip would be randomly selected from a distribution N {0, 2, 4, …} or N{1, 3, 5, …) according to the side of the roadway on which the origin and the destination are located, this roadway being considered as a single, linear one.

Depending on the design and facilities of the road (link) to be crossed there are crossing options for each link: outside any crossing facilities (mid-block), on marked crosswalk at mid-block, at junction (junction 1 or junction 2, crosswalk-marked or traffic controlled). By means of the set of the estimated crossing probabilities, a set of crossing choices can be attributed to a pedestrian . These would then be weighted by the non-uniform crossing probability distribution for the entire trip, to obtain the final crossing probability distribution.

After that, a crossing location would be randomly selected as the 1st crossing to be made along the trip. Once this selection is made, the chosen location would be considered as the origin of the rest of the trip, and the crossing probabilities would be re-calculated for the new trip. According to the total number of crossing selected, a location would be selected for each crossing and the modelling process would restart from the selected crossing location.

Accordingly, an amount of exposure would be assigned to each crossing option, which would enable the total exposure along the trip to be estimated, taking account also of “secondary” crossings. This approach, combining both traffic and epidemiological elements, would make it possible to aggregate risk exposure along real pedestrian trips passing through different micro-environments.

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Table 1. The hierarchical crossing behaviour model for a single link - Overview of crossing options, variables and values

NESTED LOGIT MODEL (Chu et al., 2001)			**Level 1**		**Level 2**					
Variable	**Definition**	**Coefficient**	**J**	**M**	J1	J2	B	C	D	F
Constant	1	1.0000	2.2332				2.2079		1.7266	1.3875
Walking distance	M	-0.0112			●	●	●	●	●	●
Crossing distance	M	-0.0089			●	●	●	●	●	●
Origin + destination both at mid-block or both at junction	1, 0	1.5722		●						
Origin at mid-block and destination at junction	1, 0	0.8415		●						
Traffic volume	Veh/h	-0.0003					●	●	●	●
Crosswalk (zebra)	1, 0	1.0002			●	●	●	●	●	●
Traffic signal	1, 0	0.7502			●	●				
Pedestrian signal	1, 0	1.2350			●	●				
Voj		0.7585	●							
Vom		0.8342		●						

•: value to be entered

Table 2. Probabilities for the primary crossing options of trips A, B, C

Trip A o/d=1

Link	Location	Probability	Distance from Origin	% trip distance	Non uniform probability distribution	**Final probabilities**	**Scaled probabilities**
Link1	J1	0.109	0	0.0	0.579	0.063	0.066
	MB	0.101	35	10.6	0.402	0.041	0.043
	J2	0.790	70	21.2	0.261	0.207	0.218
Link2	J1	0.854	75	22.7	0.244	0.209	0.221
	MB	0.103	130	39.4	0.105	0.011	0.011
	J2	0.043	190	57.6	0.056	0.002	0.003
Link3	J1	0.526	195	59.1	0.057	0.030	0.032
	MB	0.280	225	68.2	0.077	0.022	0.023
	J2	0.194	260	78.8	0.134	0.026	0.027
Link4	J1	0.044	265	80.3	0.145	0.006	0.007
	MB	0.093	295	89.4	0.228	0.021	0.022
	J2	0.864	330	100.0	0.358	0.309	0.327
						0.946	**1.000**

Trip B o/d=2

Link	Location	Probability	Distance from Origin	% trip distance	Non uniform probability distribution	**Final probabilities**	**Scaled probabilities**
Link1	J1	0.310	0	0.0	0.579	0.179	0.306
	MB	0.381	95	26.4	0.206	0.078	0.134
	J2	0.310	190	52.8	0.059	0.018	0.031
Link2	J1	0.044	195	54.2	0.057	0.002	0.004
	MB	0.093	240	66.7	0.072	0.007	0.011
	J2	0.863	290	80.6	0.147	0.127	0.217
Link3	J1	0.864	295	81.9	0.158	0.137	0.233
	MB	0.093	325	90.3	0.237	0.022	0.037
	J2	0.044	360	100.0	0.358	0.016	0.027
						0.586	**1.000**

Trip C o/d=2

Link	Location	Probability	Distance from Origin	% trip distance	Non uniform probability distribution	**Final probabilities**	**Scaled probabilities**
Link1	J1	0.109	0	0.0	0.579	0.063	0.097
	MB	0.101	35	10.8	0.399	0.040	0.063
	J2	0.790	70	21.5	0.258	0.204	0.315
Link2	J1	0.475	75	23.1	0.240	0.114	0.176
	MB	0.051	162.5	50.0	0.064	0.003	0.005
	J2	0.475	255	78.5	0.132	0.063	0.097
Link3	J1	0.864	260	80.0	0.143	0.123	0.191
	MB	0.093	290	89.2	0.226	0.021	0.032
	J2	0.044	325	100.0	0.358	0.016	0.024
						0.647	**1.000**

Table 3. Exposure for the primary crossing options of trips A, B, C.

	Trip A	**Main trip roadway 1**				**Main trip roadway 2**				**Turning movements**			
	Location	Volume	speed	time	**exposure**	volume	speed	time	**exposure**	volume	speed	time	**exposure**
Link1	J1	50	50	3.6	0.050								
	MB	50	50	3.6	0.050								
	J2 (L)	50	50	3.6	0.050								
Link2	J1 (L)	50	50	3.6	0.050								
	MB	50	50	3.6	0.050								
	J2	50	50	3.6	0.050								
Link3	J1	550	40	5	0.764								
	MB	550	40	5	0.764								
	J2	550	40	5	0.764								
Link4	J1	680	35	5	0.944								
	MB	680	35	5	0.944								
	J2	680	35	5	0.944								

	Trip B	**Main trip roadway 1**				**Main trip roadway 2**				**Turning movements**			
	Location	Volume	speed	time	**exposure**	volume	speed	time	**exposure**	volume	speed	time	**exposure**
Link1	J1	200	35	3.6	0.198								
	MB	200	35	3.6	0.198								
	J2	200	35	3.6	0.198								
Link2	J1	550	40	5	0.764								
	MB	550	40	5	0.764								
	J2 (L)	550	40	5	0.764					100	25	5	0.139
Link3	J1 (L)	680	35	5	0.944								
	MB	680	35	5	0.944								
	J2	680	35	5	0.944								

Trip C **Main trip roadway 1** **Main trip roadway 2** **Turning movements**

	Location	Volume	speed	time	**exposure**	volume	speed	time	**exposure**	volume	speed	time	**exposure**
Link1	J1	50	35	3.6	0.050								
	MB	50	35	3.6	0.050								
	J2 (L)	50	35	3.6	0.050								
Link2	J1 (L)	500	40	3.6	0.496	500	40	3.6	0.992				
	MB	500	40	3.6	0.496	500	40	3.6	0.992				
	J2 (L)	500	40	3.6	0.496	500	40	3.6	0.992				
Link3	J1 (L)	680	35	5	0.944								
	MB	680	35	5	0.944								
	J2	680	35	5	0.944								

Table 4. Exposure for the secondary crossings of trips A, B, C.

	Trip A	**Main trip roadway 1**				**Main trip roadway 2**				**Turning movements**			
	Location of secondary crossing	Volume	speed	time	**exposure**	volume	speed	time	**exposure**	volume	speed	time	**exposure**
Origin side	1 (L)	500	40	3.6	0.496	500	40	3.6	0.992				
	2	600	35	5.0	0.833								
	3	130	35	5.0	0.181								
Destination side	1 (L)	500	40	3.6	0.496	500	40	3.6	0.992				

	Trip B	**Main trip roadway 1**				**Main trip roadway 2**				**Turning movements**			
	Location of secondary crossing	Volume	speed	time	**exposure**	volume	speed	time	**exposure**	volume	speed	Time	**exposure**
Origin side	1 (L)	500	40	3.6	0.496	500	40	3.6	0.992	180	25	3.6	0.179
Destination side	1	450	40	5.0	0.625								
	2	100	35	3.6	0.099								
	3 (L)	530	40	3.6	0.526	400	45	3.6	0.794	50	25	3.6	0.050

	Trip C	**Main trip roadway 1**				**Main trip roadway 2**				**Turning movements**			
	Location of secondary crossing	Volume	speed	time	**exposure**	volume	speed	time	**exposure**	volume	speed	time	**exposure**
Origin side	1 (L)	500	40	3.6	0.496	500	40	3.6	0.992				
	2 (L)	50	35	3.6	0.050								
Destination side	1 (L)	550	40	5.0	0.764					100	25	5.0	0.139
	2 (L)	530	40	3.6	0.526	400	45	3.6	0.794	50	25	3.6	0.050

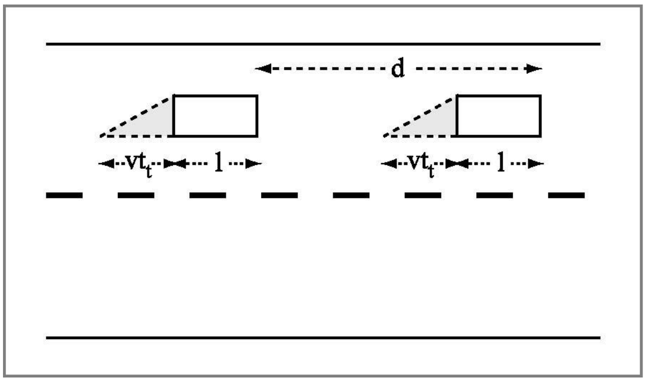

Figure 1: Indicator by Routledge, Repetto-Wright and Howarth (following Howarth)

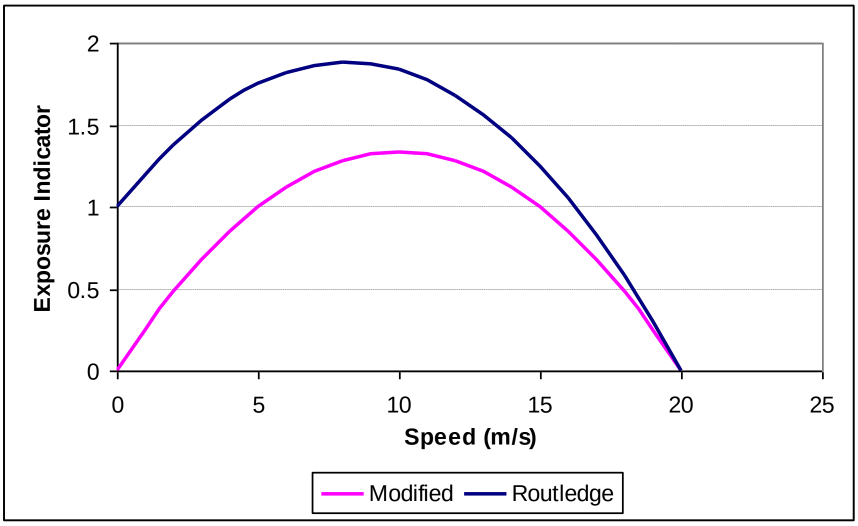

Figure 2. Routledge and modified indicators function of speed (m/s) with vf= 20 m/s, l = 5 m., tc = 2 s. with a linear function speed/density.

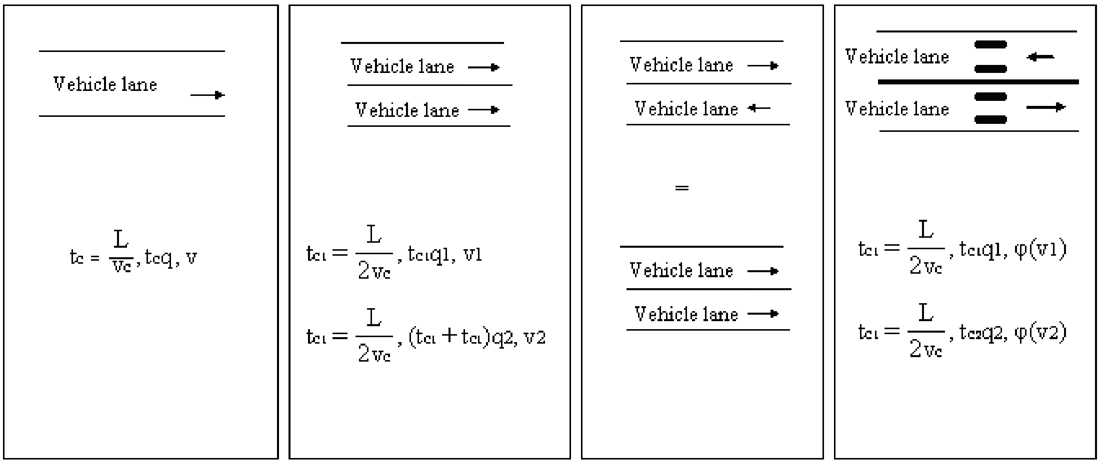

Figure 3. Crossing situations and exposures for mid-block locations.

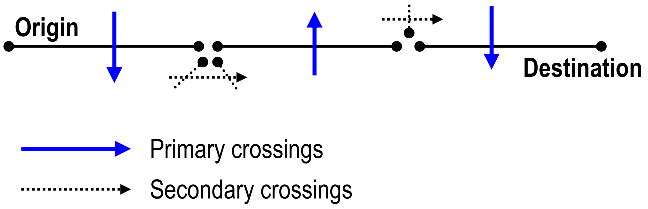

Figure 4a. “Primary” and “secondary” crossings along a pedestrian trip

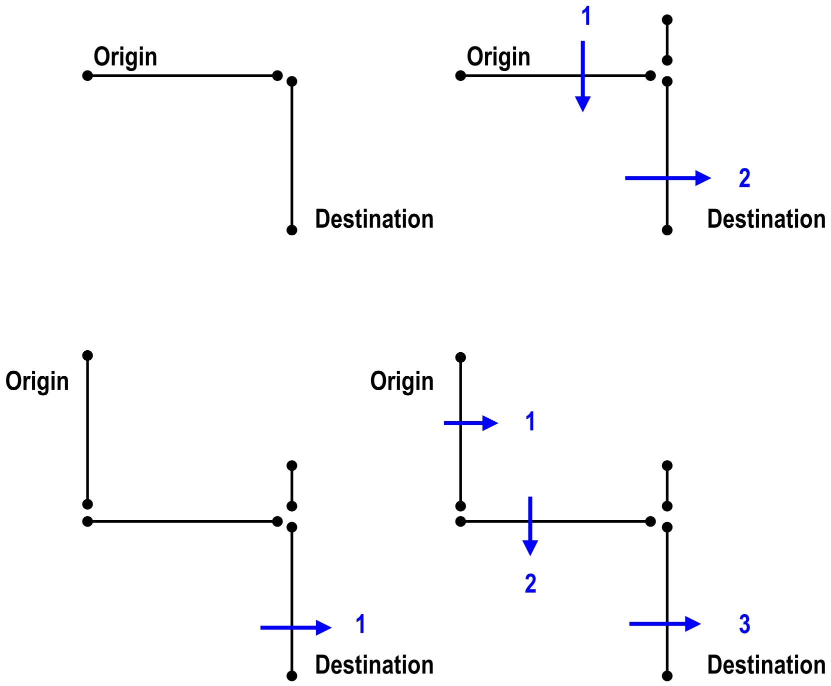

Figure 4b. Number of “primary” crossings along a pedestrian trip

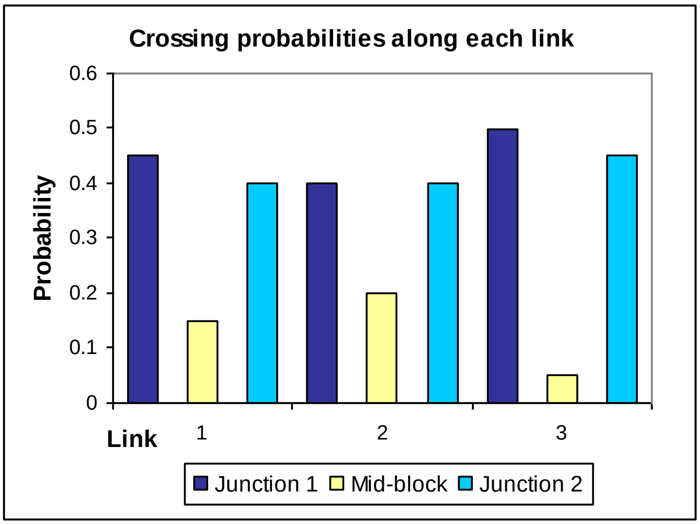

Figure 5. Model results: crossing probabilities (junction or mid-block) along three road links

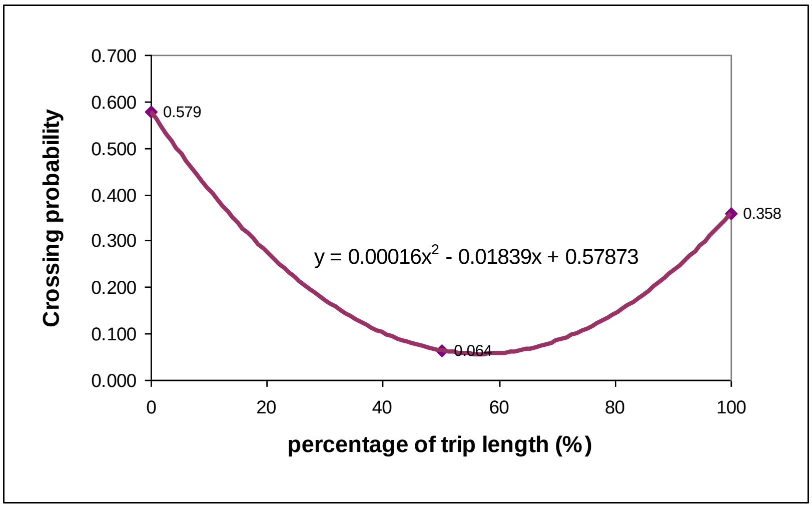

Figure 6. Non - uniform crossing probability along a trip

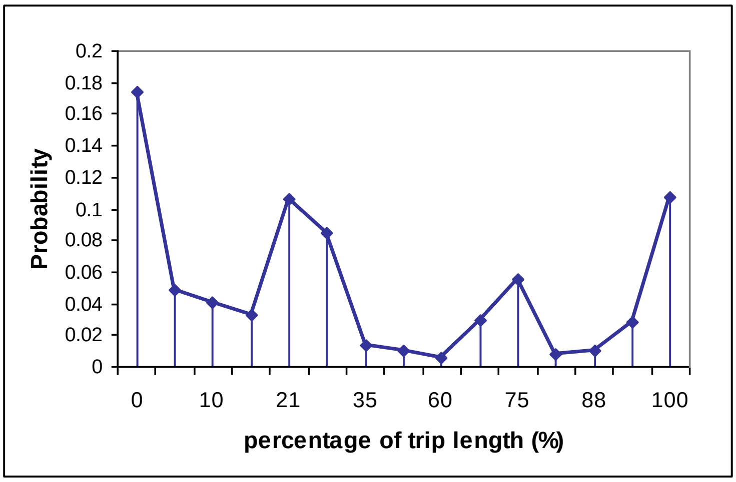

Figure 7. Final crossing probability distribution along a pedestrian trip

Figure 8.1-8.2. Origin, path, destination of trips A, B, C on the study area - Pedestrian facilities in the study area.

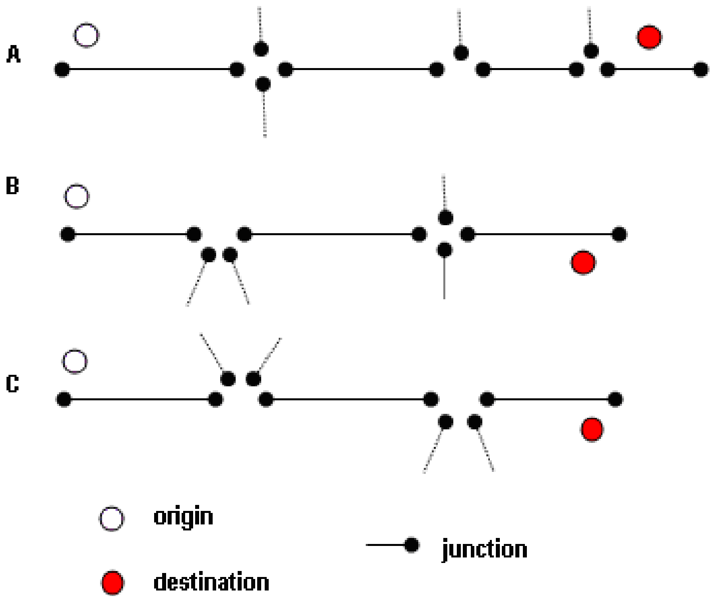

Figure 9. Representation of origin, path and destination of trips A, B, C on a single direction

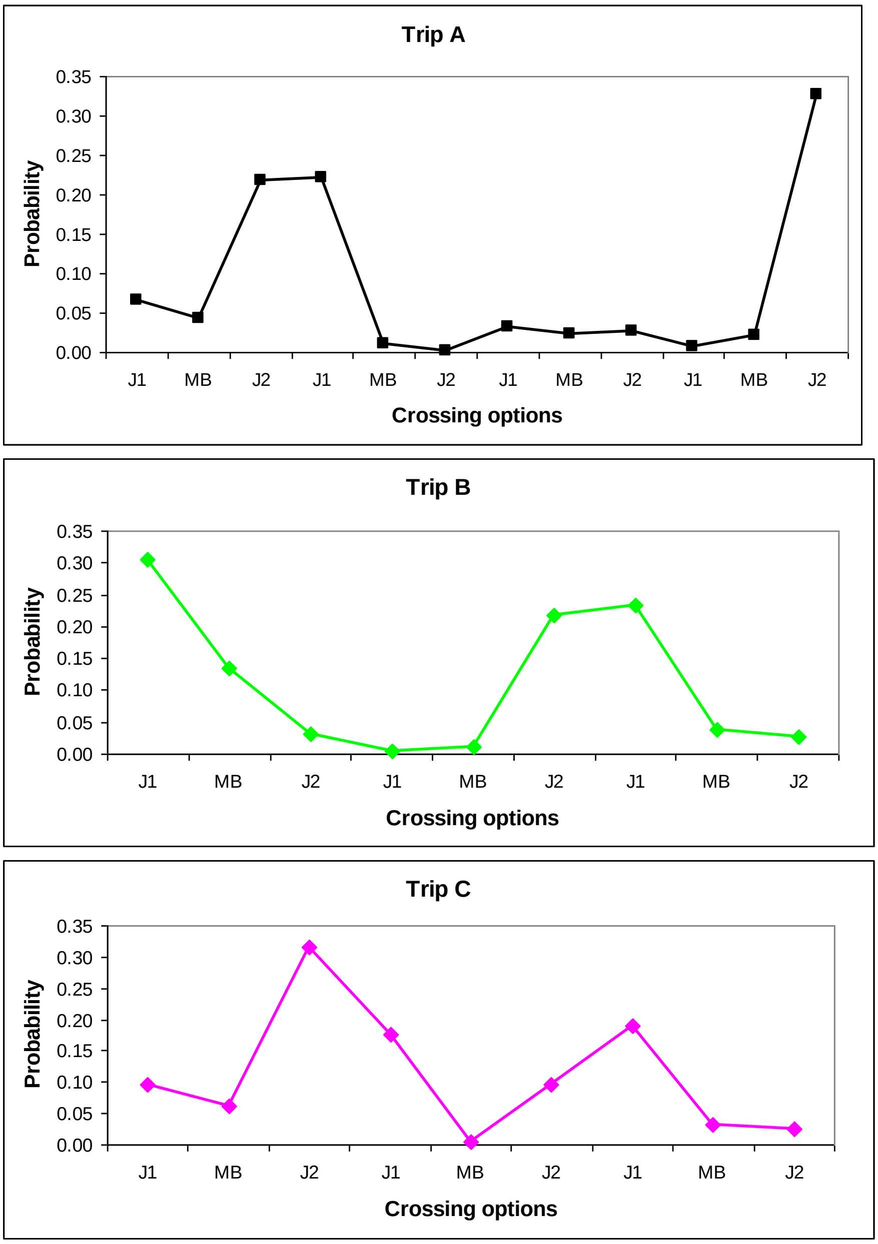

Figure 10. Final (scaled) crossing probability distribution for trips A, B, C.