A critical assessment of pedestrian behaviour models

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Abstract
This paper concerns a review and critical assessment of the existing research on pedestrian behaviour in urban areas, focusing on two separate yet complementary aspects: route choice and crossing behaviour. First, an exhaustive review of the existing route choice models for pedestrians is presented. It is shown that the existing models are mainly more stochastic and more macroscopic than required and seldom incorporate the interactions between pedestrians and traffic. Second, the existing models on pedestrians crossing behaviour are presented and assessed. It is shown that, although their approach is usually detailed, deterministic and traffic-oriented, they are mainly devoted to a local level behaviour and focus on only one type of all the potential determinants. Most importantly, these two complementary and possibly interdependent aspects of pedestrian behaviour are always examined separately. The results of this review reveal a lack of an overall and detailed consideration of pedestrian behaviour along an entire trip in urban areas. Moreover, the need for an integrated approach based on flexibility, disaggregation and more determinism is identified. Accordingly, a set of modelling techniques are discussed as a general framework for further research in the field.

Key-words: pedestrians; route choice; crossing behaviour; modelling.

1. Introduction

Previous research on pedestrians' movement in urban environment is extensive and ranges from pedestrian flow modelling to individual pedestrians' behaviour. In order to model pedestrian movement, it is necessary to consider the activity agenda of pedestrians and incorporate the interactions between pedestrians and their environment (roadway, traffic and crowd). A complicated decision making process is involved, in which pedestrians perceive and assess their environment, decide their strategy and adapt it accordingly if necessary. However, pedestrians' behaviour may not always be based on a simple stimulus-response process, but may also be strongly related to human factors. Moreover, in contrast to vehicles flows, which are distributed along fixed corridors of the road environment and are subject to specific traffic rules, pedestrian flows are characterized by a significant degree of randomness, so that one could consider that each individual's trip is unique. Consequently, pedestrians' behaviour may be far more flexible and adaptable than motorists'.

Existing research on pedestrian movement and behaviour models focuses on two separate aspects of pedestrian behaviour: route choice and crossing behaviour. Route or itinerary choice models concern pedestrians' decision making process as regards the optimal path between an origin and a (fixed or not) destination, among a number of alternatives, under some constraints. The problems examined mainly concern crowd and evacuation dynamics, with particular emphasis on congestion, bi-directional flow and bottleneck situations. These are mainly modelled by means of simulation techniques, which may be macroscopic or microscopic, discrete or continuous, time- or event-based. Moreover, the simulation rules may be stochastic, based on logical assumptions or derived from statistical modelling.

Crossing behaviour models concern pedestrians' decision making as regards the time and / or location of road crossings. These appear to be largely governed by either the gap acceptance theory, according to which each pedestrian has a critical gap to cross the road, or utility theory, according to which the utility of each alternative is a latent concept which is modelled as a random variable depending on the attributes of the alternative and the characteristics of the decision-maker. An important number of studies have been published, examining different aspects of road crossing at various locations and in different conditions. These are mainly based on ordinary probabilistic or deterministic models, calibrated by means of observational data.

In this paper, the existing researches on pedestrians' route choice and crossing behaviour are reviewed and assessed. In particular, Section 2 summarizes the existing pedestrian movement models, whereas Section 3 summarizes the existing crossing behaviour models. An exhaustive literature review was carried out on that purpose, within scientific Journals and conference Proceedings, research projects reports or publications of international organisations, as well as other studies in the field of transportation and road safety, dealing with pedestrian route choice and road crossing behaviour. From the results of the review, a number of issues arise with respect to both conceptual and practical aspects of pedestrians modelling that need to be addressed in further research. In particular, these issues are highlighted in Section 3, where the need for a different approach is discussed and a framework for integrating the various aspects of pedestrians' behaviour in urban areas is proposed. Finally, in Section 4, modelling and data issues within the proposed framework are discussed in light of the available modelling techniques.

2. Assessment of models of pedestrian movement and route choice

2.1. Literature review

Pedestrian movement in urban areas is mainly examined by means of simulation techniques. In most cases, analyses are devoted to either route choice / activity scheduling models or crowd / evacuation models. As regards evacuation models, a thorough review can be found in Xiaoping et al. (2009); in this paper, however, the review is limited to transport-related studies. Modelling techniques may range from macroscopic to microscopic simulations, of continuous or discrete time, of time- or event-based transition. The simulation rules are often based on basic kinematics or traffic flow theory, although in more microscopic approaches they are mostly derived from literature results or observational data. Model-driven rules are seldom used, due to the stochastic nature of most models.

The models developed are often macroscopic and based on traffic flow or queuing theory, or in fluid or continuum mechanics. Hunt and Griffiths (1991) developed macroscopic models for delay acceptance in pedestrians' movement on the basis of decision matrices, in relation to vehicles traffic volumes. Mitchell and Smith (2001) analyzed series, merge, and splitting topologies of pedestrian queuing networks and developed an analytical approximation methodology for computing network performance measures. Hughes (2002) proposed a continuum theory for pedestrians flow in large crowds, in which the crowd is seen as an entity that behaves rationally under the aim at achieving immediate goals (rather than an overall goal) in minimum time. This model was reformulated by Huang et al. (2009), demonstrating that it satisfies the reactive dynamic user equilibrium principle, which is often used in more microscopic models. Daamen et al. (2005) calibrated the fundamental traffic flow diagrams for pedestrian crowds inside and upstream bottlenecks, and proposed that a disaggregation of the crowd upstream the bottleneck into homogenous crowds may allow them to be described by fundamental diagrams.

However, the majority of existing pedestrian movement models concerns microscopic ones, in which collective phenomena are modelled through the analysis and aggregation of individual - level information. Early meso- and microscopic pedestrian models were mainly developed in Cellular Automata. In Cellular Automata, pedestrians move on a grid of cells; a set of rules defines the state / occupation of a cell in dependence of the neighbourhood of the cell, and a transition matrix is used to update the cell states in successive time steps.

Gipps and Markjo (1985) developed a simulation tool for the movement of pedestrians within and around buildings, by means of a rather simple set of rules. In particular, route choice was based around the concept of intermediate destinations, according to which pedestrian trips include a set of intermediate decision making nodes; these nodes may correspond to either intermediate trip points or to obstacles and other objects encountered along the trip. Moreover, the concept of 'shortest perceived path' is introduced, according to which the perceived trip distance is a function of pedestrian characteristics and stimulation sources. Within this context, the selection of successive nodes is stochastic.

Another early stochastic microsimulation tool was developed by Borgers and Timmermans (1986), concerning pedestrians movement and route choice within city centres and shopping areas. Most simulation rules were based on existing findings from the literature. The total number of stops during each trip, the type of goods and the sequence of goods to be purchased, as well as the locations where the stops take place are determined by drawing at random from successive frequency distributions. However, route choice between these locations is based on subjective utility as a function of objective characteristics and is estimated by means of a multinomial logit sub-model. The models were calibrated and validated using data from the city of Maastricht.

Løvås (1994) presented the stochastic microscopic simulation tool EVACSIM, devoted to modelling the evacuation dynamics under two basic assumptions: first, any pedestrian facility can be modelled as a network of walkway sections and second, pedestrian flow in this network can be modelled as a queuing network process, where each pedestrian is treated as a separate flow object, interacting with other objects. Walking behaviour is seen as governed by headtimes between pedestrians in high densities and by walking speed in low densities, and both parameters are considered as functions of density. An event-based markovian evacuation process is assumed, based on a sequence of conditional probabilities.

Blue and Adler (2001) modelled three distinct phenomena in bi-directional pedestrian walkways: separated flow, which is the analogous of two unidirectional flows, interspersed flow, in which pedestrians find their way through a crowd without forming distinct directional flow lanes and dynamic lane formation, where lanes are not fixed but emerge from interactions between pedestrians. A cellular automaton was used to model the behaviour of individual pedestrians, seen as autonomous entities, by means of a limited set of rules describing features of pedestrian behaviour such as side-stepping, conflict mitigation and temporary stand-off. However, walking speed was considered to be randomly distributed. Fundamental parameters of pedestrian flow were generated after testing a broad range of densities.

In another stochastic microsimulation tool for bi-directional flows in cellular automaton, a different approach was followed (Burstedde et al, 2001). In this case, a dynamic grid underlying the static grid occupied by the pedestrians was considered. The static grid does not evolve with time or with the presence of pedestrians and is solely used to specify the walking space, whereas the dynamic grid is modified by the presence of pedestrians, has its own diffusion and decay coefficient and is used to model interactions between pedestrians. The occupation of the static grid is modified on the basis of a probabilistic transition matrix of the dynamic grid.

Within the same framework, Weifeng et al (2003) developed a bi-directional pedestrian flow microsimulation tool, by considering the following evolution for the system: a freely moving state when density is low, a self-organization into several lanes when density increases and a merging of all lanes into two large lanes as density further increases. A number of basic behavioural features, such as backward movement and lane changing are also allowed. Default probabilities are assigned for pedestrians' movement in case the cell ahead is occupied. Moreover, Lee and Lam (2008) calibrated a simulation model for bi-directional pedestrian flow at crosswalks, mainly through the exploitation of simulation rules and equations tested in previous studies, together with some rules derived from observational data. The model was extended to provide pedestrian level-of-service results at signalised crosswalks.

Liu et al. (2000) extended the DRACULA micro-simulation model to simulate individual pedestrian and vehicle movements and their interactions in a network of highways and walkways and to incorporate a number of pedestrian and vehicle responsive signal control strategies. Two types of pedestrians are defined, law-obeying and opportunistic ones, and both are considered to follow fixed routes on a walkway network of links and nodes. Different crossing rules are attributed to each type of pedestrians, while interactions with drivers may also be considered; however, drivers and pedestrians decisions are based on default probabilities. The model was demonstrated on a signalized junction, on which different signal strategies were tested.

Finally, Wakim et al. (2004) proposed a Markovian model of pedestrian movement of four discrete states: standing, walking, jogging and running, on the basis of existing results on speed distribution. The model was tested for the Renault pedestrian trajectory scenarios and was also used to demonstrate vehicle - pedestrians accident risk at road crossing situations.

During the last decade, more advanced microscopic simulation techniques are exploited, namely multi-agent simulation systems, which are based on artificial intelligence concepts. In these systems, pedestrians are treated as fully autonomous entities with cognitive and often learning capabilities.

Dijkstra and Timmermans (2002) conceptually outline a multi-agent system that can be used for simulating pedestrian behaviour; this system includes a Cellular Automaton to represent the virtual network and sets of autonomous agents of different type that navigate in the virtual environment network, each with their own behaviours, beliefs and intentions. Batty and Jiang (1999) developed a series of multi-agent models which operate in cellular space and demonstrated that global patterns emerge as a consequence of positive feedback and learned local behaviour, in which pedestrians explore the local properties of space purposefully en route to their destinations.

Under these principles, Kukla et al, (2001) developed the PEDFLOW simulation tool for pedestrian movement, in which an agent-activation cycle includes the following steps: direction determination, observation, parameterisation of observation, rule evaluation and movement. Direction determination is based on a shortest-path rule, whereas parameterisation and evaluation are based on sets of discrete ordered options for distance, speed and direction (e.g. 'same' or 'different'). Moreover, pedestrian-agents are allowed to interact with other agents (pedestrians, other attractors etc.). Video recordings of pedestrians negotiating short road sections in city centres were used to obtain the basic rules.

Teknomo (2006) used multiagent simulation for the investigation of pedestrians space allocation and found that the direct relationship assumption of space and flow in the macroscopic level does not always stand and that the movement quality of pedestrians can be improved by controlling the interaction between pedestrians. These findings were based on a simple multiagent tool of basic kinematics (acceleration / deceleration) and physical (forward or repulsive) forces. The system was developed on the basis of real world data and was used to test scenarios on lane formation at crosswalks and the effect of elderly pedestrians on the system performance.

Osaragi (2004) suggests that pedestrian walking behaviour is partly result of 'mental stress', which is defined as a combination of shortest path criteria and perception of the environment, and partly result of occasional elements, such as pursuing behaviour, halting to avoid collision, foreseeing collisions and overtaking. Non linear regression models were developed for the quantification of 'mental stress' factors and linear regression models were developed for the quantification of occasional factors. Video recordings of pedestrian movements in a train station were used on that purpose. A multiagent simulation tool was developed examining comfort and efficiency of pedestrian space.

Kitazawa and Batty (2004) used multi-agent simulation to explore the shortest-path rule and utility maximization of pedestrians in shopping areas. Four stages are considered in each agent-activation cycle: the first one concerns information gathering and comparison with that from previous cycle and the second one uses marketing data in conjunction with neural network algorithms to identify the attractiveness of each location to each pedestrian provided in the form of a probability being chosen. At the third stage, the optimal route is chosen under time constraints; a mixed logit model is the basis of the optimization, which can be further refined by introducing travelling salesman algorithms. Finally, the fourth stage concerns local movement and is simple based on obstacle avoidance. A Genetic Algorithm is used for the optimization of the system, on the basis of extensive video recordings of pedestrian shoppers in Tokyo.

In another research dealing with walking behaviour (Hoogendoorn, 2004) pedestrians are treated as adaptive controllers that minimize their subjective cost of walking. The multiagent system developed is based on a physical model and a control model; the physical model is based on ordinary physical and friction forces, whereas the control model is used to model the acceleration process. A cost optimization process is considered, in which costs (disutility) are expressed as a function of control-drifting cost, proximity cost and acceleration cost. Moreover, pedestrian impatience is considered. The system can represent various empirically observed macroscopic characteristics of pedestrian flows, such as bottleneck situations and dynamic lane formation in evacuations.

Hoogendoorn and Bovy (2004) also deal with the walking behaviour, which refers to route choice and activity scheduling, by means of a utility maximization under uncertainty principle. The NOMAD multiagent simulation system is based on dynamic estimation of a continuous stochastic dynamic optimal. The basic assumption of this approach is that pedestrians decision making is hierarchically structured and that utilities at lower levels influence utilities at higher levels. Pedestrians minimize the running costs (expected travel time, obstacles, planned speed, expected interactions, stimulations) and the terminal costs (penalties of delays), while adapting their activity scheduling. A basic difference from classical discrete choice theory lies in the fact that in infinite number of alternative routes is available and uncertainty in the route is considered.

A more probabilistic approach to modelling pedestrians walking behaviour is proposed by Antonini et al. (2006), by means of discrete choice analysis. The set of choices results of a combination of walking alternatives on the basis of three factors: speed (same speed, accelerate, decelerate), radial direction (eleven alternatives) and number of other pedestrians present. Cross-nested logit models and mixed logit models are tested, yielding similar systematic utility functions. The models were calibrated by means of video sequences of actual pedestrian movements next to an entrance of a metro station in Lausanne. A microsimulator was created on the basis of these models. The same framework was further developed by Robin et al. (2009), considering two distinct scenarios: an unconstrained one, and a constrained one on the basis of leader-follower and collision avoidance assumptions. The models were validated with datasets representing both uncontrolled and controlled experimental conditions. However, no related simulation framework is proposed.

One of the few researches that consider the interaction with traffic in pedestrian crossing movement was presented by Airault et al (2004). In the ARCHISIM microscopic simulation tool, pedestrians are considered to move along virtual lanes and manoeuvring around obstacles is examined; within this framework, traffic is considered as another obstacle met by pedestrians. In vehicle / pedestrian interactions, pedestrians' options include deceleration and deviation, whereas vehicles options include deceleration only. In a recent research (Doniec et al. 2008), this simulation tool was used to model pedestrian movements at intersections and roundabouts, while dealing with several issues involved in multi-agent simulation.

Finally, a recent research (Gaud et al. 2008) proposes a hierarchical consideration of the complex systems describing pedestrians walking behaviour in urban areas, through a multilevel multi-agent simulation technique, capturing different levels of attractions (and thus interactions) for pedestrians walking in urban areas and allowing transitions from macroscopic to microscopic levels. However, the research is mainly focused on the description of the system design, processes and performance, whereas simulation results in terms of pedestrians behaviour are not reported.

2.2. Models assessment

The main features of the approaches and models presented in the above review are summarized in Table 1, sorted according to the methodology used, from macroscopic to more microscopic methods. It is noted that, although the basic methods and tools used are common, the purposes of the analyses vary significantly. In general, most pedestrian movement models deal with crowd and evacuation dynamics, and the interaction between pedestrians and traffic is seldom explored. Even within the context of crowd analyses, existing efforts often focus on local phenomena, such as bottlenecks, counterflows and dynamic lane formation.

Table 1 to be inserted here

In the majority of cases, pedestrians movements are determined on the basis of basic kinematic or traffic flow equations, whereas the more detailed behavioural features are based on assumptions or ad hoc rules, not always derived from actual observations. Within this framework, some over-simplifications can often be identified.

This uncertainty is further attributed to the fact that little or no validation of these tools is available. Most available researches concern a demonstration of interesting and promising ideas, usually based on emerging techniques, and in which validation of results is included in the future plans. It is also noted that, even when observational data are exploited for models development, the calibration from the validation process is not adequately separated.

Moreover, the majority of methodological approaches identified are stochastic ones, ranging from fully Markovian approaches, to occasional use of probabilistic or deterministic sub-models, aiming to capture a particular aspect of pedestrians movement or decision-making. These stochastic approaches are meaningful when dealing with pedestrian movement in crowds or shopping areas; however, it is likely that the movement of pedestrians in the road network, seen in equivalence to the movement of vehicles, can be explained and monitored by specific determinants.

For instance, it would not be reasonable to assume that the path or crossing locations chosen by pedestrians in urban areas are randomly selected, regardless of roadway, traffic and crowd conditions encountered and individual characteristics. On the contrary, a number of researches have identified and quantified factors affecting pedestrians' decisions in different circumstances in urban areas. The following section summarizes the main findings in this field.

3. Assessment of pedestrian crossing behaviour models

3.1. Literature review

Numerous researches deal with the behaviour and movement of pedestrians at junctions and / or at other crossing locations. An important part of these researches concerns the evaluation of roadway design, traffic control features and road safety treatments by means of before-and-after studies on pedestrians observed behaviour and safety. Other statistical analyses are based on gap acceptance models, level of service models or discrete choice models, calibrated by means of observational data or stated preference data.

It is noted that numerous additional observational studies of pedestrians behaviour in specific urban areas are available e.g. by national or local transport planning or road safety authorities. In this review, only studies that explicitly deal with road crossing behaviour and include some statistical analysis or modelling are examined, while priority is given to scientific publications and other research reports. A useful review of (mostly earlier) studies on pedestrians crossing behaviour in terms of gap or delay acceptance can be found in Ishaque and Noland (2007).

A number of pedestrian mobility and safety treatments have been evaluated with positive results, including the implementation of measures prompting motorists to yield for pedestrians (Koenig and Wu, 1994, Nasar, 2003), in conjunction with advance stop lines and pedestrian-activated amber flashing lights (Van Houten, Malenfant, 1992), the construction of speed humps downstream uncontrolled pedestrian crosswalks (Dixon et al. 1997), the implementation of fluorescent strong yellow-green pedestrian warning signs at mid-block locations (Clark et al. 1996), the construction of a refuge island (Nee and Hallenbeck, 2003), the use of waiting countdown timers at traffic controlled junctions (Keegan and O'Mahony, 2003) the implementation of systems for detecting pedestrians near the crosswalk zone and for warning drivers (Hakkert et al., 2002) or providing an earlier activation or an extension of the pedestrian stage (Carsten et al., 1998).

Moreover, pedestrian road crossing is often incorporated in multi-modal level-of-service analyses (Winters et al. 2001). In several related researches, measures of effectiveness for crossing at junctions were proposed (Sarkar, 1995, Crider et al., 2001), difficulty to cross was proposed as a measure of effectiveness for mid-block locations (Baltes and Chu, 2002) and pedestrians' road crossing options were seen as measures of accessibility to transit (Phillips et al. 2001).

Although these results are very useful from a traffic engineering and policy viewpoint, they incorporate behavioural elements in a macroscopic way only. Several authors argue that, despite the improvements of the road and traffic features creating a safer environment, the unsafe behaviour of pedestrians is less affected (Hakkert et al. 2002, Nee and Hallenbeck, 2003). It is therefore necessary to further analyze the behaviour of pedestrians itself, in order to better integrate it into the traffic features evaluations. Within this context, an important number of researches deal with the behaviour of pedestrians in terms of crossing decisions and the related determinants.

Some of these concern psychological and behavioural analyses. Hine (1996) used in-depth interviews to identify pedestrians' perception as regards difficulty to cross and assessment of traffic conditions and crossing facilities in the centre of Edinburgh. Evans and Norman (1998) developed hierarchical regression models for road crossing behaviour, by means of completed questionnaires which included scenarios of three specific potentially dangerous road crossing behaviours; pedestrians stated crossing behaviour was then modelled in relation to measures of attitude, subjective norm, perceived behavioural control, self-identity and intention. Yagil (2000) proposed multivariate regression models for the self-reported frequency of unsafe crossings in relation to beliefs regarding the consequences of the behaviour, instrumental and normative motives for compliance with safety rules, and situational factors. Diaz (2002) developed a structural equations model explaining pedestrians risk-taking behaviour on the basis of attitude, subjective norm, perceived control, behavioural intention and reported violations, errors and lapses. Self-reported crossing behaviour data from pedestrians in the city of Santiago was used on that purpose. Holland and Hill (2007) tested for age and gender differences in road crossing decisions within a theory of planned behaviour analysis including intention, situation and risk perception effects.

It is obvious that these analyses have little or no practical applicability in terms of describing crossing behaviour in urban areas. Although the knowledge of the psychological factors related to unsafe behaviour is important and useful, it is more likely that the roadway and traffic conditions have an additional, and maybe more important effect on the crossing behaviour of pedestrians. A number of road and traffic oriented approaches can be identified within this framework, and these are mainly based on gap acceptance and utility theory.

Himanen and Kulmala (1988) used discrete choice techniques to model the probabilities of a driver braking or weaving and of a pedestrian continuing to cross in driver/ pedestrian encounters at pedestrian crosswalks. Multinomial logit models were developed on the basis of video recordings on pedestrian crossings in Helsinki. The results also allowed for the calculation of safety margins in driver/ pedestrian interactions. The explanatory variables included the number of vehicles in the platoon, vehicle speed, pedestrian distance from kerb, number of pedestrians simultaneously crossing and city size, whereas road width, median refuge, yield rules and most of the pedestrian variables were not found to be significant. It is noted, though, that the reaction of the other user is included in neither the drivers' nor the pedestrians' model.

Hine and Russel (1993) investigate the relationships between traffic conditions and pedestrian behaviour, which determine the extent of barrier effects, either physical (actual barriers to movement) or psychological (perceived impediments to movement) ones. The data used were collected by means of video recordings of pedestrian movements and vehicles speed and traffic flow along a road with no pedestrian facilities, as well as by interviews with pedestrians reporting their perception of the environment, in Edinburgh. The results included calculation of crossing ratios and crossing angles under different conditions. The authors concluded that traffic conditions and the barrier effects often led pedestrians to taking different routes or switching to other transport modes, instead of walking.

Oxley et al. (1997) examined the crossing behaviour of elderly pedestrians at mid-block locations by measuring a number of indicators such as kerb delay, gap acceptance, crossing time, time-of-arrival, minimum safety margin and crossing style (non-interactive vs. interactive). Measurements for elderly pedestrians were compared to those of younger ones by means of t-tests. Results showed that elderly pedestrians present increased kerb delay, and accept larger gaps; however they also frequently adopt unsafe interactive crossing styles. A related study (Bernhoft and Carstensen, 2008) revealed that older pedestrians appreciate sidewalks and crossing facilities much more than younger pedestrians. Rosenbloom et al (2008) used a similar method to examine the crossing behaviour of children and found that not looking was the most prevalent unsafe behaviour, followed by the combination of not looking and not stopping, and not stopping before crossing. They also found that children accompanied by an adult committed more unsafe behaviours, especially when not holding hands with the adult.

Hatfield and Murphy (2007) investigates the effect of mobile phone use on pedestrians crossing behaviour, by comparing different groups of pedestrians and found that pedestrians who crossed while talking on a mobile phone crossed more slowly, and were less likely to look at traffic before starting to cross or while crossing.

Varhelyi (1998) investigated drivers' giving-way and speed adaptation at mid-block crosswalks, under the assumption that the speed behaviour of drivers approaching a crosswalk depends on pedestrian’s arrivals, which in turn are related to vehicles' expected arrivals. Drivers' speed behaviour was videotaped and measured using speed guns and speed profiles were created; measurements at crosswalks with pedestrians' presence were compared to those without pedestrians' presence by means of t-tests. The results showed very low proportions of drivers giving-way to pedestrians; a consistent pattern was observed, according to which drivers may maintain high speed or even accelerate in order to warn pedestrians of their intention not to give-way. Moreover, the drivers' decision zone was identified at around 50 metres before the crosswalk.

Another relevant research (Hamed, 2001) deals with modelling pedestrian crossing behaviour at mid-block locations on divided and undivided roads, using data collected in the city of Amman, Jordan. First, pedestrian kerb waiting time is modelled as a survival model i.e. a risk function giving the instantaneous failure rate (ceasing the waiting time) assuming the pedestrian has not successfully crossed at a given time point. A time-dependent baseline risk is compared to an exogenous variables generated risk. Additionally, the number of crossing attempts was modelled under Poisson and Negative Binomial assumptions in relation to waiting time. Explanatory variables included gender, age, crossing frequency, number of people in the group, access to private vehicle, destination, home location and previous accident involvement; surprisingly, traffic parameters were not found to be statistically significant. The models results suggest that pedestrians waiting times and number of crossing attempts are strongly related. Moreover, it was shown that, in divided roads, pedestrians behave differently from one side to the median, than from median to the other side of the road.

An interesting approach for modelling pedestrians crossing behaviour at mid-block locations concerns a crossing difficulty model (Baltes and Chu, 2002), leading to a level of service designation at mid-block locations. In this research, participants rated the difficulty to cross at several mid-block locations in a continuous scale from 1 to 6 without actually crossing. The ordinary least squares statistical method was used to develop an analytical crossing difficulty model in relation to personal, roadway, crosswalks and traffic control characteristics. Modelling results showed that the levels of crossing difficulty tend to increase with the width of painted medians, signal spacing, and turning movements, whereas they tend to decrease with the presence of traffic and pedestrian signals.

One of the very few researches comparing the crossing preferences of pedestrians among various alternatives was presented by Chu et al. (2002), based on discrete choice theory and models. In particular, a crossing scenario was presented to survey participants for stating their crossing preferences for a single road link between the following options: 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 also has a two-level structure; the top level has two branches: a junction branch and a mid-block branch, and the bottom level has two options in the junction branch and four options (cross first – walk later, jaywalk, walk first – cross later, use mid-block crosswalk) in the mid-block branch. Explanatory variables mainly focus on the road environment. As expected, the model yields higher probability for crossing at junctions compared to mid-block locations. Moreover, it allows for the quantification of the effect of road features on the crossing location selected by pedestrians. An attempt of extending this model to estimate pedestrians crossing preferences along an entire trip is presented in Lassarre et al. (2007).

A similar approach for modelling pedestrians crossing decisions through utility theory is described by Hui and Hongwei (2008), where a choice between crossing at or outside crosswalk is modelled in relation to willingness to detour, detour distance, perceived safety level at crosswalk, compliance, travel time and the relative values of safety, convenience and time. The proposed model appears to be appropriate for application at trip level, although no such results are provided by the authors.

Simpson et al. (2003) investigate crossing decisions of children and young adults at mid-block locations. An experimental virtual environment was generated for the measurement of participants' decisions under various conditions. A number of indicators were measured and compared by means of t-tests, including collisions and "tight fits" (e.g. near collisions), cautious crossings, crossing times, accepted and rejected gaps and total number of gaps. Results indicated that young pedestrians' road crossing decisions are based on traffic gaps rather than vehicle speed. Moreover, the number of unsafe road crossings decreases with age.

Sun et al. (2003) proposed a framework for modelling vehicle - pedestrian interactions at uncontrolled mid-block crosswalks, based on two distinct and interrelated phenomena: pedestrians' gap acceptance and motorists yield behaviour. As regards pedestrians gap acceptance, three modelling approaches were tested: a deterministic model relating gap acceptance to gap size, a probabilistic model treating gap acceptance as a random variable from a certain distribution, and a binary logit approach explaining pedestrians gap acceptance through age, gender, waiting time, gap size, and number of pedestrians waiting on the kerb. As regards motorists yield behaviour, two approached were tested: a discrete probability model (i.e. the fraction of the number of yielding vehicles to the total number of vehicles) and a binary logit model. In both cases, the binary logit model had better performance. The two models were linked with a System Dynamic Interaction (SDI), in which motorist - pedestrian interaction can be modelled as a two-player non-zero-sum non-cooperative game.

Muraleetharan et al (2004) proposes a method to estimate the overall level-of-service of sidewalks and crosswalks on the basis of total utility values, which come from a conjoint analysis. Pedestrians were surveyed at four locations around Hokkaido University, Japan, and their perceptions of the ease of walking on a sidewalk or crosswalk were scaled from 1 to 10. A linear relationship was assumed between the total utility of a sidewalk / crosswalk and the overall level-of-service of that sidewalk / crosswalk. Three levels-of-service were considered (resulting from a coupling of the classical levels-of-service A, B, C etc.) in relation to road width and separation, obstructions, flow rate, bicycles traffic, opposing events, space at corner, crossing facilities, turning vehicles and pedestrians delay. Conjoint analysis was used to calculate utility values for each level. Results revealed a significant correlation between total utility and pedestrians' perception, suggesting that the total utility values can be used to predict the overall level-of-service of sidewalks. However, no conclusions could be drawn as regards crosswalks.

Das et al. (2005) estimated gaps distribution by means of both parametric and non-parametric techniques. The non-parametric estimation concerned a smoothed monotone regression method to estimate the distribution of critical gaps among pedestrians. The parametric estimation was based on ordered probit modelling, in relation to traffic composition, median, and the presence of other pedestrians. The models were developed on the basis of video recordings at signalized junctions in New Delhi. The results showed that pedestrian behaviour varies depending on whether the pedestrian is initiating a crossing from the sidewalk or is continuing a crossing from the median, confirming thus previous findings. Moreover, pedestrians appear to behave more cautiously when facing larger vehicles. It is noted, though, that this research does not consider drivers' response to pedestrians behaviour. Additionally, the effect of waiting times or of number of crossing attempts on the critical gap distribution is not examined.

Oxley et al. (2005) investigated age differences in the ability to choose safe time gaps in traffic as well as some of the factors involved in such judgements in a simulated road-crossing task. Participants decision times were compared by means of ANOVA. A logistic regression model was then developed for gap selection, in relation to walking time, age group, time (or distance) gap and vehicle speed. Results showed that a large proportion of the elderly pedestrians opted for unsafe traffic gaps, given their walking times. Moreover, all participants crossing decisions appeared to be based primarily on the distance of oncoming vehicles and to a lesser extent on time of arrival.

In a laboratory experiment (TeVelde et al. 2005) participants were presented with a road inside the laboratory on which a bike approached with different speeds from different distances, and were asked both to verbally judge whether they could cross the road, and to actually walk across the road. Three measures of behaviour were considered, namely the percentage of crossings, the number of unsafe errors, and the number unnecessarily rejected gaps. These were analyzed and compared by means of ANOVA techniques. Results did not fully confirm previous findings on age effects, as younger individuals appear to be more cautious. Moreover, all participants appeared to use a strategy based both on the distance and the speed of the approaching bike, and adjusted their crossing time to the time-to-arrival of the bike. Eventually, a binary variable for crossing decisions was expressed as a non linear function of vehicle approach times.

Yang et al. (2006) proposed a micro-simulation model of pedestrians' crossing behaviour, compliance and gap acceptance, which includes the effect of policeman, other pedestrians and vehicles. It represents the behaviour of two types of pedestrians (law-obeying ones and opportunistic ones, with possibility to shift from one group to the other under specific conditions) when facing red light at junctions. The model was calibrated on the basis of questionnaire responses and video recordings of pedestrians in China, and was validated on the basis of further video recordings. However, the effects of the various crossing behaviour determinants were not statistically quantified.

3.2. Models assessment

It can be deduced that an important number of studies have provided insight into several aspects of pedestrians crossing behaviour and have also contributed in the quantification of the related determinants, although mainly focusing one a particular set of determinants in each case. These studies described above are summarized in Table 2. It can be seen that several observational studies do not include model development; in these studies, basic statistical analysis is typically carried out e.g. for comparisons between groups of pedestrians with different characteristics in terms of observed behaviour.

Table 2 to be inserted here

Most importantly, crossing behaviour is examined at or around specific locations, e.g. junctions or other crossing facilities or other uncontrolled locations, whereas practically no methods or results are available on trip level. Even on this local level, the analyses do not examine crossing decisions between alternative locations, but solely focus on the various aspects of a crossing decision at a specific location e.g. gaps rejected, number of attempts, compliance to pedestrian rules etc.

Nevertheless, a pedestrian moving along a road segment is faced with a number of crossing alternatives, from which he or she shall select crossing locations. This selection is affected by characteristics of the trip (e.g. the origin and destination, the complexity and the length of the route), characteristics of the infrastructure (e.g. pedestrian facilities, road geometry and traffic conditions), as well as individual characteristics (e.g. age and gender, risk proneness, delay acceptance etc.). The selected crossing options shall therefore reflect the combined assessment of the above features under specific conditions. Certainly, one should allow a degree of randomness in crossing behaviour. However, it would not be reasonable to assume that pedestrians crossing decisions are independent of the number and type of crossing alternatives along the trip and the other internal and external factors.

4. The need for an integrated approach

From the above literature review, it can be seen that route choice and crossing behaviour are two aspects of pedestrian behaviour that are always treated separately. The objectives and methods used in the analysis of each of these two issues are different. In brief, it can be said that existing models on pedestrians' movement and route choice are mainly simulation-based, they are most often stochastic, they are oriented towards crowd dynamics and they seldom incorporate the interactions between pedestrians and traffic. On the other hand, crossing behaviour models are usually more detailed, they are based on probabilistic or deterministic models and they are traffic-oriented; however, they are mainly devoted to a local level behaviour and usually focus on a particular type of determinants.

The assumption that the two aspects of pedestrian behaviour in urban areas are separate is quite realistic. However, the fact that they are separate should not imply that they are independent. On the contrary, there are reasons to assume that route choice and crossing behaviour may be linked in most cases. In order to elaborate this idea, it is useful to start from a hierarchical structure of pedestrian activities in urban areas, suggested by Hoogendoorn (2004) and further discussed by Airault et al. (2004) and Ishaque and Noland (2007). In this approach, pedestrian behaviour is considered to follow a three-level structure, as shown in Figure 1. In this section, this hierarchy shall be further analyzed, highlighting several dependences among behavioural levels.

Figure 1 to be inserted here

In particular, the highest level concerns strategic decisions, such as the choice of departure time and the elaboration of an agenda of activities; this level corresponds to off-road activities i.e. decisions made before the trip. The second intermediate level concerns tactical decisions, such as activity scheduling, choice of activity area and route choice. The second level may concern both off-road and on-road decisions; for instance, the knowledge of the road network may affect route choice before the trip, however the conditions encountered during the trip may further determine or modify this choice. The final third level concerns operational decisions involved in the walking task. This third level corresponds to on-road decisions i.e. decisions that are made during the trip. Moreover, the walking task concerns several components, including obstacle avoidance, interaction with other pedestrians and certainly road crossing. The present analysis shall focus on the on-road part of the decision making process.

The classification of route choice in the tactical level and of the crossing behaviour in the operational level is intuitive. However, as mentioned above, tactical decisions can be reconsidered on the basis of the conditions encountered along the trip. In particular, components of the tactical level may be influenced by and interact with components of the operational level. Previous research has shown that, in response to adverse traffic conditions, pedestrian routes are changed, walking is rescheduled or abandoned, and crossing locations change (Hine, 1996). Moreover, pedestrians may select to postpone an activity or avoid a specific activity area if a crowd is expected to be present at the area, in order to avoid negotiating the crowd. Moreover, pedestrians adjust their route in a way that minimizes the obstacles to be encountered (e.g. they may select the sidewalk with the least commercial activities). Finally, pedestrians may select their route also on the basis of the number and type of crossing facilities available.

As shown in Figure 1, the dependence between tactical and operational decisions can be further distinguished into traffic-related dependences and crowd-related dependences. It is thereby considered that there the interaction between activity area choice and obstacle avoidance is a crowd-related dependence, whereas the interaction between route choice and crossing behaviour is mostly a traffic-related dependence.

In particular, among different alternatives, the route along which a higher number of protected pedestrian crossings are available may be more attractive to pedestrians for whom safety and comfort are essential. Additionally, a route along roads with less traffic and less pedestrian facilities may be opted for by pedestrians that adopt mid-block crossing and jaywalking in order to minimize their delay. In general, therefore, the conditions expected or encountered as regards road crossing may be a determinant of the route chosen by pedestrians, regardless of whether this process is carried out beforehand or evolves during the trip. A more analytical presentation of pedestrians' behavioural levels can therefore be considered, following the above discussion, and this is presented in Figure 1.

According to this approach, the tactical level of pedestrians' behaviour receives feedback from the operational level activities and conditions. In particular, a degree of dependence among route choice and crossing behaviour is considered. This suggests that the characteristics of the route chosen define the number and type of crossing alternatives available to a pedestrian moving along the route. Moreover, the number and type of crossing options may be an additional factor contributing to the selection of a particular route against the alternative routes.

In practice, this idea translates into an exchange of roles between independent and dependent variables in models building. In particular, it suggests an incorporation of route characteristics as explanatory variables into crossing decision models and accordingly, an incorporation of crossing option characteristics as explanatory variables into route choice models. The consideration of a hierarchical model on the basis of the proposed structure, taking into account the related interactions would therefore be interesting.

The above approach requires a partly deterministic approach, as it aims to the quantification of the effects and interactions considered. In the available literature, however, route choice models are seldom non-stochastic. Evidently, it is often difficult to express the complexity and the dynamics of pedestrian movement in an algebraic model of pedestrian movement; therefore, simulation seems to be an appropriate modelling approach to develop a model of pedestrian destination, route choice and sequencing behaviour (Timmermans et al.1992). Moreover, as mentioned above, a degree of randomness in pedestrian movement should be allowed.

Nevertheless, previous research has shown that there are specific factors that may affect pedestrians route choice such as distance or time, the number of obstacles or interactions with other pedestrians along the route, the directness of the route (i.e. the number of directional changes), the level-of-service provided by the roadway and traffic environment, the overall attractiveness of the environment, and so on (Hoogendoorn, Bovy, 2004). Moreover, Li and Tsukaguchi (2005) suggest that other additional factors should be taken into account in route choice models, namely those related to road network topology. In particular, results from a GIS analysis of Oipa city, Japan indicated that pedestrian route choice behaviour varies according to the topology of the origin and the destination; moreover, one-route origin-destination pairs may exist, and these may be affected by the network grid degree, the number of road links that radiate from the start point, and the network density. A similar idea is outlined by Lassarre et al. (2007), according to which a finite number of alternative routes is available between a given origin and destination, and the number and type of crossings also depend on the layout of the route. Therefore, models capturing the effect of these or other additional factors could be formulated and incorporated in route and crossing sequencing algorithms.

As regards crossing behaviour, further research should also focus on the consideration of decision sequences, i.e. the consideration of crossing decisions along a trip. The available results on local level shall certainly be useful within this framework. Moreover, it is important that all types of related determinants are identified and quantified, including individual, roadway, traffic and trip characteristics.

5. Discussion

This paper suggests that, unlike most existing studies, further research on pedestrian route choice models should be based on more flexibility, more disaggregation and non-(fully)-stochastic processes. Moreover, crossing behaviour modelling should be expanded to address decision making along entire pedestrian trips in relation to individual, roadway, traffic and route characteristics. Finally, the interdependence among route choice and crossing behaviour should be captured and expressed by the models, through the incorporation of crossing options attributes into route choice models and of route attributes into crossing decision models. Obviously, the formulation and estimation of such models would not be straightforward and is far beyond the scope of the present research. However, with a combination of appropriate modelling techniques, adapted to the modelling structure discussed above, it should be possible to obtain useful and meaningful results.

Within this framework, *discrete choice models* (Ben-Akiva and Lerman, 1985) appear to be an appropriate family of models for describing pedestrian route choice and crossing behaviour, as they allow for both disaggregate and (partly) deterministic analysis. Moreover, a broad range of techniques is available, enabling the consideration of hierarchical processes, including ordered, nested or crossed models. More specifically, the nature of pedestrian decisions among a combination of alternatives brings about a need to relax the independence assumptions of these alternatives, inducing dependences that may only be captured by either cross-nested models or mixed models. Moreover, the dynamics of pedestrian decision making processes along trips can also be examined by means of discrete choice models, either as typical "panel" effects (e.g. agent heterogeneity) or as state dependence, expressing thus the dependence among sequential similar decisions of the pedestrian along a trip. As regards the simulation framework, which would allow for the description of pedestrians movement, most researchers agree that *multi agent simulation* is an appropriate technique for pedestrian modelling (Dijkstra and Timmermans, 2002, Bierlaire et al. 2003). Apart from the microscopic and dynamic modelling they offer, the fact that pedestrians - agents may be given a variety of vision, cognition and learning capabilities renders these systems far more advantageous than ordinary simulation environments. Moreover, these systems may accept complex and very detailed rules, and their properties are in full accordance with those of discrete choice models. It is stressed, though, that the simulation should be based on discrete choice modelling results, rather than observational data or other ad hoc considerations.

Moreover, a number of issues need to be examined in pedestrian multiagent simulation, including the purpose for which the model is built, the extent to which the model is rooted in independent theory, the extent to which the model can be replicated, the ways the model might be verified, calibrated and validated, the way model dynamics are represented in terms of agent interactions, the extent to which the model is operational etc. (Crooks et al. 2008).

Summarizing, further research is needed for (combined) modelling of route choice and crossing behaviour of pedestrians in urban areas. The present research analyzed a number of questions related to these two aspects of pedestrians' behaviour, revealing a lack of complete and comprehensive modelling approach. A pedestrian behaviour hierarchical scheme is proposed as a general framework for further research. It is noted that, although the proposed hierarchical structure includes various pedestrian decisions and activities, this research emphasizes on route choice and crossing behaviour, those two being considered to require the most future effort.

A final remark concerns the type and amount of data required for the development of the models and the validation of a simulation framework. Although most existing studies apply some automatic analysis of video recordings, this does not cover all aspects of data collection, as it focuses mainly on local behaviour, given the narrow range of a surveillance camera (Bierlaire et al. 2003). Obviously, this type of data is not appropriate for analyzing in detail the behaviour of pedestrians along entire trips. A few studies, mainly in the field of transport geography, use observations from following pedestrians along a route (Lassarre et al. 2005), or combine these with interview results (Hine and Russel, 1993, Fitzpatrick et al. 2004). Such approaches are more often used in exposure analyses in environmental epidemiology. In such an approach, pedestrians would be followed during their trip and their decisions would be recorded (route, crossings, interactions with traffic and/or other pedestrians), while at the same time the characteristics of the roadway and traffic environment would be noted. Consequently, the probability of pedestrians choosing each alternative crossing location along a trip would be modelled in relation to individual characteristics (e.g. age, gender), roadway characteristics (e.g. shoulder width, roadside parking, number of lanes, median, marked crosswalks, traffic signals) and traffic conditions (e.g. low/high traffic volume). It is likely that such survey methods would be much more promising within the proposed hierarchical behaviour framework.

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Table 1. Review of the existing pedestrian movement models

		Problem			Methodology			Simulation framework							Interactions				
								Time model		System Transition		Rules							
Author	Year	traffic flow	crowd / evacuation	route choice / wayfinding	macroscopic	microscopic (Cellular Automata)	microscopic (MultiAgent)	Continuous	discrete	time-based	event-based	traffic / kinematic	logical / literature	Models driven	Other pedestrians	Road environment	obstacles	Traffic	Observational Data
Hunt and Griffiths	1991	●			●			●		●			●	●		●		●	●
Mitchel and Smith	2001	●			●			●			●	●		●	●	●			
Hughes	2002	●			●										●	●			●
Daamen et al.	2005	●			●										●		●		●
Huang et al.	2009	●			●										●				
Gipps and Markjo	1985			●		●			●	●		●	●		●		●		
Borgers and Timmermans	1986			●		●			●	●			●	●		●			●
Løvås	1994		●			●			●		●	●			●		●		
Blue and Adler	2001		●			●			●	●			●		●		●		
Burstedde et al.	2001		●			●		●	●	●		●	●		●		●		
Weifeng et al .	2003		●			●			●	●			●		●				
Liu et al.	2000			●		●			●	●			●	●	●	●		●	
Wakim et al.	2004			●		●			●	●			●					●	
Lee and Lam	2008			●		●			●	●		●	●		●				●
Dijkstra and Timmermans	2002			●			●		●	●			●		●	●	●		
Batty and Jiang	1999		●	●			●		●	●		●	●		●	●	●		●
Kukla et al.	2001		●	●			●		●	●		●	●		●	●	●		●
Teknomo	2006		●				●		●	●		●		●	●		●		●
Osaragi	2004		●				●		●	●		●		●	●		●		●
Kitazawa and Batty	2004			●			●		●		●			●	●	●	●		●
Hoogendoorn	2004		●				●	●		●		●		●	●		●		
Hoogendoorn and Bovy	2004			●			●		●	●		●		●	●	●	●		●
Antonini et al.	2006			●			●		●	●		●		●	●		●		●
Airault et al.	2004			●			●		●	●		●	●		●	●		●	
Robin et al.	2009			●											●		●		●
Doniec et al.	2008			●			●		●	●			●		●	●		●	●
Gaud et al.	2008			●			●		●	●		●	●		●	●		●	

Table 2. Review of the existing pedestrian crossing behaviour models

		Problem					Context		Theory			Models				Level		Variables			Data	
Author	**Year**	before-and-after	crossing decision yes/no	how to cross	where to cross	driver/pedestrian interaction	engineering	psychology	Gap Acceptance	Level-of-Service	Utility	Stochastic	Linear Regression, GLM	Discrete choice model	Other	local	trip	individual	roadway	traffic	observational data	self-report
Koenig and Wu	1994	●					●									●			●	●	●	
Nasar	2003	●					●									●			●	●	●	
Van Houten, Malenfant	1992	●					●									●			●	●	●	
Dixon et al.	1997	●					●									●			●	●	●	
Clark et al.	1996	●					●									●			●	●	●	
Nee and Hallenbeck	2003	●					●									●			●	●	●	
Keegan and O'Mahony	2003	●					●									●			●	●	●	
Hakkert et al.	2002	●					●									●			●	●	●	
Carsten et al.	1998	●					●									●			●	●	●	
Winters et al.	2001			●			●			●						●			●	●		
Sarkar	1995			●			●			●						●			●	●		
Crider et al.	2001			●			●			●						●			●	●		
Phillips et al.	2001			●			●			●						●			●	●		
Rosenbloom et al.	2008			●			●		●				●			●		●			●	
Berhhoft and Carstensen	2008			●			●	●	●				●			●		●	●			●
Hine	1996		●	●				●	●						●	●		●	●	●		●
Evans and Norman	1998		●	●				●			●		●			●		●				●
Yagil	2000		●					●	●				●			●		●				●
Diaz	2002		●	●				●	●						●	●		●				●
Holland and Hill	2007		●	●				●	●				●			●		●				●
Himanen and Kulmala	1988		●	●		●	●		●		●			●		●			●	●	●	
Hine and Russel	1993		●	●			●	●	●						●	●			●	●	●	●
Oxley et al.	1997		●	●			●		●						●	●		●		●	●	
Varhelyi	1998		●			●	●		●						●	●				●	●	
Hatfield and Murphy	2007			●			●		●				●			●		●		●	●	
Hamed	2001		●	●			●		●				●			●		●	●	●	●	
Baltes and Chu	2002		●				●			●			●			●		●	●	●		●
Simpson et al.	2003		●	●			●		●						●	●		●		●	●	
Sun et al.	2003		●			●	●		●		●	●		●		●		●		●	●	
Muraleetharan et al.	2003		●	●			●	●		●	●				●	●		●	●	●		●
Das et al.	2005		●	●			●		●				●	●		●			●	●	●	
Oxley et al.	2005		●	●			●		●				●			●		●		●	●	
TeVelde et al.	2005		●	●			●		●				●			●		●		●	●	
Chu et al.	2002				●		●				●			●		●	●	●	●	●	●	
Lassarre et al.	2007				●		●				●			●		●	●	●	●		●	
Hui and Hongwei	2008				●		●				●			●		●	●	●	●		●	

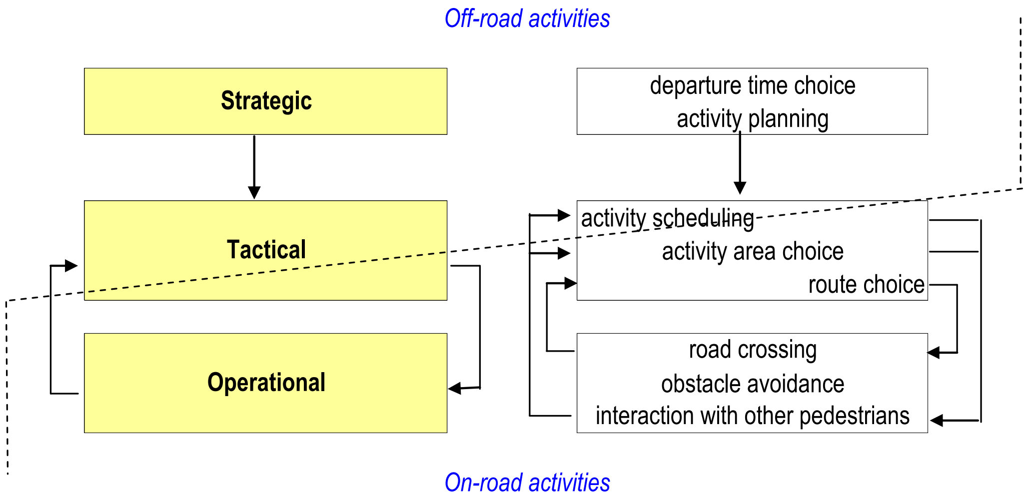

Figure 1. Pedestrian behavioural levels, activities and interactions