Road Safety and Simulation
International Conference
RSS2013

October 22-25, 2013
Rome, Italy

Challenges in Simulation of Pedestrians and Motorised Traffic

Eleonora Papadimitriou
Post Doctoral Researcher
National Technical University of Athens
Department of Transportation Planning and Engineering
5 Heroon Polytechniou str., GR-15773 Athens
nopapadi@central.ntua.gr, *Phone: +302107721380, Fax:+302107721454*

Jean-Michel Auberlet
Researcher
IFSTTAR - *Institut français des sciences et technologies des transports, de l'aménagement et des réseaux, LEPSIS*
Cité Descartes - *14-20 bd Newton, 77447 Champs-sur-Marne* - *Marne-la-Vallée Cedex 2*
jean-michel.auberlet@ifsttar.fr, *Phone: +33240845613*

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

Sylvain Lassarre
Research Director
IFSTTAR - *Institut français des sciences et technologies des transports, de l'aménagement et des réseaux, GRETIA*
Bâtiment Le Descartes 2, 2, rue de la Butte Verte, F-93166 Noisy le Grand cedex
Sylvain.lassarre@ifsttar.fr, *Phone: +33145925764*

ABSTRACT

The objective of this paper is the analysis of the state of the art in pedestrian simulation models and the identification of key issues for further research, with particular focus on the modelling of pedestrians and motorised traffic. A review and comparative assessment of pedestrian simulation models is carried out, including macroscopic models, earlier meso- and miscosimulation models (mostly in Cellular Automata) and more recent Multi-Agent simulation models. The models reviewed cover a broad range of research topics: pedestrian flow and level of service, crowd dynamics and evacuations, route choice etc. However, pedestrian movement in urban areas and the interactions between pedestrians and vehicles have received notably less attention. A number of challenges to be addressed in future research are outlined: first, the need to and account for the hierarchical behavioural model of road users (strategic / tactical / operational behaviour); second, the need for appropriate description and parameterization of vehicle and pedestrian networks and their crossing points; third, the need to exploit in the simulation models the results of statistical and probabilistic models, which offer valuable insight in the determinants of pedestrian behaviour. In each case, recent studies towards addressing these challenges are outlined.

Keywords: pedestrian; behaviour; simulation.

BACKGROUND AND OBJECTIVES

The analysis of pedestrian movement in urban areas and their interaction with motorized traffic may allow researchers and traffic managers to understand the behaviour of road users and their response to various strategies or interventions, and eventually to more efficient and targeted planning of pedestrian facilities and traffic control in urban areas, and more accurate estimation of pedestrian safety level.

Pedestrian movement is subject to fewer constraints and traffic rules compared to vehicle’s movement. The complex and dynamic nature of pedestrians movement and decision making in urban areas can not be easily addressed by means of algebraic models, and therefore simulation often appears to be a more appealing modelling approach (Bierlaire et al. 2003; Timmermans et al. 1992). However, simulation models of pedestrian movement have been criticised for lacking the explanatory power required to enable their exploitation for planning and engineering purposes (Papadimitriou et al. 2009). On the other hand, the pedestrian simulation models embedded in general software packages (e.g. vissim, aimsun) are not adequately documented. In fact, numerous studies have identified determinants of pedestrian behaviour in terms of road, traffic and human factors; however, these results are seldom exploited in simulation modelling (Ishaque & Noland, 2008).

Within this context, the objective of this paper is the analysis of the state of the art in pedestrian simulation models and the identification of key issues for further research, with particular focus on the modelling of pedestrians and motorised traffic. First, a literature review of existing pedestrian simulation models is carried out. Then, the existing models are assessed and a number of key issues and challenges for improvement of existing models are proposed. In each case, recent studies with recommendations and examples for addressing these challenges are briefly described.

REVIEW OF PEDESTRIAN SIMULATION MODELS

In this section, a review of existing pedestrian simulation models is carried out. The review is an update and improvement of the review presented in Papadimitriou et al. (2009). The pedestrian simulation techniques analysed range from macroscopic to microscopic simulations, of continuous or discrete time, of time- or event-based transition. The related research topics cover traffic flow and level of service, crowd and evacuations, route choice etc.

The review is representative of past and current trends in pedestrian simulation; however it is not exhaustive, especially as regards crowd and evacuation simulation, where a great number of studies are available. Given that the scope of this paper is to focus on simulation studies on vehicle / pedestrian interaction, only the main aspects of crowd simulation are presented. For more comprehensive reviews on this particular topic the reader is referred to Duives et al. (2013).

Macroscopic models

Macroscopic models are based on traffic flow or queuing theory, or in fluid or continuum mechanics. A comparative assessment of macroscopic pedestrian simulation studies is presented in Table 1.

Table 1 Overview of macroscopic pedestrian simulation models

					Simulation framework											
		Problem			Time model		System Transition		Rules			Interactions				
Author	**Year**	traffic flow	crowd / evacuation	route choice	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	●										●				
Jiang et al.	2012	●	●		●		●		●			●	●	●		●
Bergman et al.	2011	●											●		●	●

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 various topologies of pedestrian queuing networks and developed an analytical approximation methodology for estimating 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 in minimum time. This model was reformulated by Huang et al. (2009), demonstrating that it satisfies the reactive dynamic user equilibrium principle.

Daamen et al. (2005) calibrated the fundamental traffic flow diagrams for pedestrian crowds inside and upstream bottlenecks, and proposed a disaggregation of the crowd upstream the bottleneck into homogenous crowds.
More recently, Jiang et al. (2012) developed an extended reactive dynamic user equilibrium model of pedestrian counterflow as a continuum, allowing to observe some crowd pedestrian flow phenomena, such as dynamic lane formation in bi-directional flow.
In a different context, Bergman et al. (2011) simulated traffic and pedestrian flows in roundabouts and estimated roundabout performance in relation to pedestrian flows and crossing behaviour, using the VISSIM tool. More specifically, the number of times that vehicles had to yield for pedestrians was taken into account.

Meso- and microscopic models

Cellular Automata

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 Marksjö (1985) developed a simulation tool for the movement of pedestrians within and around buildings. 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 (i.e. intermediate trip points or obstacles). Moreover, the concept of 'shortest perceived path' is introduced, as a function of pedestrian characteristics and stimulation sources.
Borgers and Timmermans (1986) analysed 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 drawn at random from successive distributions. However, route choice between these locations is estimated by means of a multinomial logit model.
Lǿvås (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.
Helbing and Molnár (1995) introduced the 'social force' model of pedestrian crowd dynamics, according to which pedestrian movement is dominated by acceleration, attraction and separation forces, leading to self-organization of pedestrian crowd (Helbing et al., 2005).
Blue and Adler (2001) analysed bi-directional pedestrian walkways in three ways: as separated flows, interspersed flows (i.e. pedestrians pick their way through a crowd without forming distinct directional flow lanes - this being usually a short-term, transient group behavior), and dynamic lane formation. A limited set of rules were used for pedestrian behaviour in terms of side-stepping, conflict avoidance and temporary standing. Walking speed was considered to be stochastic.
In another study of bi-directional pedestrian flow (Burstedde et al, 2001), a dynamic grid underlying the static grid occupied by the pedestrians was considered. The dynamic grid was

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.
Moreover, Weifeng et al (2003) studied three bi-directional pedestrian flow states: 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.
Lee and Lam (2008) calibrated a simulation model for bi-directional pedestrian flow at crosswalks, mainly through the exploitation of rules and equations tested in previous studies, together with some rules derived from observational data.
Liu et al. (2000) used the DRACULA microsimulation model to simulate pedestrian and vehicle movements and their interactions in a network of highways and walkways. Two types of pedestrians were defined, compliant and opportunistic ones, and different crossing rules were attributed to each type of pedestrians. Vehicles and pedestrians were both considered to follow fixed routes and their decisions were based on default probabilities.
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 speed distributions. The model was tested for various pedestrian trajectory scenarios and was used to demonstrate vehicle - pedestrians accident risk at road crossing situations.
Yue et al. (2010) tested speed / density / flow relationships in bi-direction pedestrian flow using cellular automata simulation. Feng et al. (2013) simulated pedestrian flow while crossing on a signal-controlled crosswalk in a cellular space and calculated speed / density / flow relationships in different conditions (bi-directional flow, crosswalk size etc.). The interaction with vehicles was not taken into account, however.
An overview of existing studies is presented in Table 2.

Table 2 Overview of microscopic pedestrian simulation models in Cellular Automata

					Simulation framework											
		Problem			Time model		System Transition		Rules			Interactions				
Author	**Year**	traffic flow	crowd / evacuation	route choice	Continuous	discrete	time-based	event-based	traffic / kinematic	logical / literature	Models driven	Other pedestrians	Road environment	obstacles	Traffic	Observational Data
Gipps and Markjo	1985			●		●	●		●	●		●		●		
Borgers and Timmermans	1986			●		●	●			●	●		●			●
Lǿvås	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			●		●	●		●	●		●				●
Yue et al.	2010		●			●	●		●	●		●				●
Feng et al.	2013		●			●	●		●	●		●	●			●

Multi-agent simulation

During the last years, more advanced microscopic simulation techniques are exploited, namely multi-agent simulation systems, which are based on artificial intelligence techniques. In these systems, pedestrians are treated as fully autonomous entities with cognitive and learning abilities. Table 3 provides an overview and comparative assessment of existing pedestrian multi-agent simulatrions.

Table 3 Overview of Multi-Agent pedestrian simulation models

					Simulation framework											
		Problem			Time model		System Transition		Rules			**Interactions**				
Author	**Year**	traffic flow	crowd / evacuation	route choice	Continuous	discrete	time-based	event-based	traffic / kinematic	logical / literature	Models driven	Other pedestrians	Road environment	obstacles	Traffic	Observational Data
Batty and Jiang	1999		●	●		●	●		●	●		●	●	●		●
Kukla et al.	2001		●	●		●	●		●	●		●	●	●		●
Dijkstra and Timmermans	2002			●		●	●			●		●	●	●		
Teknomo	2006		●			●	●		●		●	●		●		●
Osaragi	2004		●			●	●		●		●	●		●		●
Kitazawa and Batty	2004			●		●		●			●	●	●	●		●
Hoogendoorn	2004		●		●		●		●		●	●		●		
Hoogendoorn and Bovy	2004			●		●	●		●		●	●	●	●		●
Antonini et al.	2006			●		●	●		●		●	●		●		●
Airault et al.	2004	●		●		●	●		●	●		●	●		●	
Godara et al.	2007	●		●		●	●		●	●			●		●	
Gaud et al.	2008			●		●	●		●	●		●	●		●	
Guo et al.	2010		●		●	●	●		●	●	●	●				●
Dai et al.	2013		●		●		●		●			●	●			●
Usher and Strawderman	2010			●	●		●			●		●	●			

Dijkstra and Timmermans (2002) described the concept of a multi-agent system for simulating pedestrian behaviour; this system includes a Cellular Automaton to represent the network, and autonomous agents of different type that navigate in the network, each with their own behaviour.
Batty and Jiang (1999) tested a series of multi-agent models in cellular space and demonstrated that global patterns emerge as a consequence of feedback and learned local behaviour.
Kukla et al. (2001) developed the PEDFLOW simulation tool for pedestrian movement. Direction determination is based on a simple shortest-path rule, but discrete ordered options are used for distance, speed and direction selection. Agents are also allowed to interact with other agents (pedestrians, other attractors etc.). Video recordings of pedestrians negotiating short road sections in city centres were used to yield the basic rules.
Teknomo (2006) developed a simple multi-agent simulation tool of basic kinematics (acceleration or 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) developed a multi-agent simulation tool examining comfort and efficiency of pedestrian space. It was assumed that that pedestrian behaviour is partly result of 'mental stress',

which is defined as a combination of shortest path criteria, perception of the environment, and occasional elements. 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.

Kitazawa and Batty (2004) used multi-agent simulation to explore the shortest-path rule and utility maximization of pedestrians in shopping areas on the basis of extensive video recordings of pedestrian shoppers in Tokyo. Four stages are considered: the first one concerns information gathering; 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 choice probability; the third stage concerns the optimal route choice under time constraints, on the basis of a mixed logit model; the fourth stage concerns local movement and is based on simple obstacle avoidance rules.

In Hoogendoorn (2004) pedestrians are considered to be adaptive controllers that minimize their subjective cost of walking. The multi-agent system developed is based on a physical model and a control model. A cost optimization process is proposed, in which costs are expressed as a function of control-drifting cost, proximity cost and acceleration cost. 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) developed NOMAD multi-agent simulation system for the analysis of pedestrian to route choice and activity scheduling, by means of a utility maximization under uncertainty theory. The system is based on dynamic estimation of a continuous stochastic dynamic optimal, on the basis of a hierarchically structured utility approach. A basic difference from classical discrete choice theory lies on the fact that an infinite number of alternative routes are available to each pedestrian.

Airault et al (2004) developed the ARCHISIM microscopic simulation tool, in which pedestrians are considered to move along virtual lanes and manoeuvring around obstacles, including motorized vehicles. In vehicle / pedestrian interactions, pedestrians' options include deceleration and deviation, whereas vehicles options include deceleration only. Preliminary results of applying the model show satisfactory conformity with reality.

Antonini et al. (2006) developed a micro-simulation tool on the basis of cross-nested and mixed logit choice models of pedestrian walking behaviour. The choice of each pedestrian results from a combination of walking alternatives on the basis of speed, radial direction and number of other pedestrians present.

Godara et al. (2007) developed a multi-agent simulation model in a cellular space, specifically devoted to modelling vehicle-pedestrian interactions and the resulting accident risk of pedestrians. Two specific aspects of pedestrians crossing decisions were taken into account, namely the attractiveness of marked crosswalks, which is defined as a ‘magnetic field’ with a given range and strength, and the crossing decision making process, which is based on a small set of simple rules.

Guo et al. (2010) proposed a semi-continuous model in which pedestrian space is continuous and pedestrian's position is discrete. Destination selection is based on a discrete choice rule of direction selection. The model was used to simulate two streams of pedestrians intersecting at-angle. The model is proved to adequately simulate the movement of dense crowds.

Dai et al. (2013) simulated the counter-flow of pedestrians through bottlenecks on the basis of four basic forces (gradient force, repulsive force, resistance force, and random force), as well as

basic speed and density equations. The model was calibrated and validated for simulating the movements of pedestrians boarding and alighting at a metro station.
Usher and Strawderman (2010) gathered a large set of validated rules of pedestrian walking behaviour and integrated them into the ISATP simulation tool. The model was tested for several pedestrian walking facilities, including a hallway and a sidewalk in different conditions.
Gaud et al. (2008) proposed a hierarchical (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 study is mainly focused on the description of the system, whereas simulation results in terms of pedestrians behaviour are not reported.
A number of issues that need to be examined in future research of pedestrian multiagent simulation are analysed in Crooks et al. (2008).

Assessment of existing models

In the majority of cases, pedestrians movements are determined on the basis of basic kinematic or traffic flow equations. In cases of crowd analysis, the ‘social forces’ (Helbing and Molnár, 1995) rules appear to be dominant. Utility maximization (cost minimization, shortest path etc.) is a very popular concept for pedestrian decision-making; however it is most often based on simple time or distance criteria.
Torrens et al. (2012) present a detailed review and testing of pedestrian movement algorithms for multi-agent simulation, classifying those under four main categories: random (e.g. random walk, Brownian movement), steering (basic kinematics), social forces (acceleration, attraction and separation), and path-planning (e.g. shortest path algorithms). The authors argue that, although none of the algorithms is realistic enough for describing pedestrian movement, each one of them may be adequate under specific conditions (e.g. social force approaches are generally reliable when analyzing crowds, path planning is acceptable for global movement but not for local movement etc). One might also add that the more detailed behavioural features (local / operational behaviour) are based on assumptions or ad hoc rules, not always derived from actual observations.
Overall, existing models do not adequately take into account the effects of various determinants of pedestrian behaviour, at least in a consistent manner. More specifically, the majority of models are fully stochastic ones (i.e. random draws), with only occasional use of probabilistic (i.e. probability-based or utility-based) or deterministic sub-models, aiming to capture a particular aspect of pedestrian behaviour. These stochastic approaches are meaningful when dealing with pedestrian movement in crowds, shopping areas etc. However, a number of studies have identified and quantified factors affecting pedestrians' behaviour and vehicle / pedestrian interactions in urban areas. These factors include roadway, traffic, crowd, and individual pedestrian’s characteristics (for detailed reviews see Ishaque and Noland, 2008 and Papadimitriou et al. 2009).
The results of this review reveal that the vast majority of pedestrian simulation models address pedestrian flow, crowd and evacuation issues, while the interaction of pedestrians and traffic is explored to a much smaller extent. This is quite surprising, given that a significant proportion of pedestrian trips and movement takes place on the road networks, with potentially important traffic and safety implications.

On the other hand, it should be acknowledged that the combined simulation of pedestrians and motorized traffic involves more methodological and practical difficulties than pedestrian flow or crowd analysis, due to:

- A larger number of restrictions in pedestrian movement on an ‘empty’ road network, compared to pedestrian movement in a ‘dedicated’ pedestrian facility (e.g. transit station, shopping centre etc.); even larger number of restrictions and interactions in pedestrian movement on a road network with vehicle traffic.
- The baseline differences in the structure and type of pedestrian and vehicle networks; vehicle networks are easily represented by links and nodes, but pedestrian trajectories are not situated on these links and nodes, but rather in their adjacent area (e.g. sidewalks). Nevertheless, vehicle networks and pedestrian trajectories are bound to intersect while road crossing, in particular in the case of the shared space.
- The different behavioural ‘levels’ involved in pedestrian movement on road the network (strategic / tactical / operational) and the need to account for their inter-relations.
- At the same time, while there are numerous studies on pedestrian road crossing, there is still a lack of knowledge and understanding of pedestrian strategies, tactics and operational decisions on the road network, especially at the presence of vehicles; shortest-path principles are more difficult to consider at more complex network topologies or at the presence of vehicles, cost-minimization needs to take into account several factors other than e.g. delays etc.

In the next section, these challenges are further analysed and concrete recommendations are proposed, together with an outline of the most recent and promising studies towards addressing these challenges.

CHALLENGES IN PEDESTRIAN SIMULATION

Considering the Hierarchical Model of Pedestrian Behaviour

The classical hierarchical model of behaviour includes three levels: strategic level, tactical level and operational level (Allen et al., 1971; Van Der Molen and Bötticher, 1988). Figure 1 presents an adaptation of this behavioural model for pedestrians.

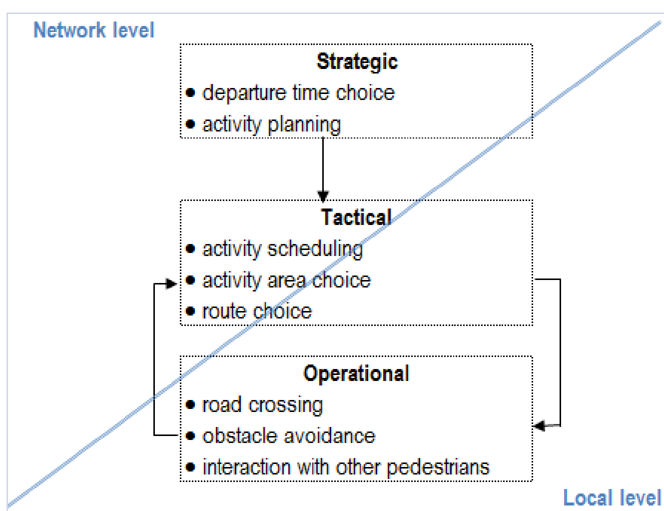

Figure 1 Hierarchical Model of Pedestrian Behaviour (adapted from Papadimitriou et al. 2009)

Typically, in the existing studies most of the strategic and tactical choice models are developed at network level, while some of the tactical choice models and all of the operational choice models are developed at local level, without taking into account their interrelations.
This approach has been implemented in the NOMAD pedestrian simulation tool (Hoogendoorn, 2004), particularly as regards route choice (at the tactical level) and walking behaviour / obstacle avoidance (at the operational level). However, this tool concerns pedestrian flow and crowd simulation and is not designed for pedestrian movement on the road network at the presence of vehicles. A hierarchical approach, taking into account the inter-relations between tactical and operational decisions in crowd microsimulation is also proposed in Bourgois and Auberlet (2012).
More recently (Xi and Son, 2012), proposed a framework for two-level simulation modelling of pedestrian movement at a junction area. The tactical level concerns the decision of a trajectory for crossing the junction (e.g. sequence of crosswalks to be used), the decision to wait for the signal display etc., while the operational level concerns the collision avoidance with other pedestrians.
Specifically for pedestrian behaviour while walking and road crossing on a road network, Papadimitriou et al. (2009), described how the interaction of choices taken at the upper level (e.g. route choice) with choices taken at the lower level (e.g. choice of a crossing location), should be addressed. Both types of choice are largely based on the balancing of pedestrian's risk acceptance vs. delay acceptance, and changes in the initial plan may occur dynamically according to the traffic conditions encountered - entire trajectories and / or specific choices (e.g. road crossing) may be reconsidered.
From a more practical viewpoint, López-Neri et al. (2010) proposed a multi-level framework for multi-agent simulation architecture in urban areas: the first level corresponds to the network description; the second level models the behaviour of various road users and the third level models the detailed behaviour of road users in terms of specific tasks or short-term plans to be executed. However, although the need to account for pedestrians is mentioned, the proposed framework was only tested for vehicle movement within different traffic signal control strategies.
Overall, there appears to be no general concensus among researchers as regards the specific components of each behavioral level. In fact, road crossing may be assigned to either the tactical or the operational level, depending on the type of network considered (e.g. isolated junction or larger area). Moreover, route choice / wayfinding may be assigned to either the tactical or the operational level, depending on the scale of analysis considered.

Parameterisation of vehicle and pedestrian networks

As mentioned above, the vehicle and pedestrian networks cannot be described by a single (common) parameterization, given that pedestrians do not move 'on', but rather 'besides' the vehicle network. The vehicle and pedestrian trajectories are intersecting only when pedestrians attempt to cross roads. In most of existing simulation models, pedestrians are either allowed to cross roads randomly in an 'empty' road network, or constrained to cross at dedicated locations (e.g. traffic controlled crosswalks) when vehicle traffic is present. Both approaches are rather unrealistic and of little usefulness for analyzing pedestrian movement in terms of e.g. safety or level of service.

Therefore, the description and parameterisation of the vehicle and pedestrian networks should be improved, with not only explicit definition of their potential crossing points, i.e. the road crossing alternative locations, where pedestrians and vehicles are expected to 'meet' and interact. The networks description should allow to simulate a shared space, to simulate pedestrians who cross the street at any point along the sidewalk etc.

First, the relationship between vehicle and pedestrian networks and trajectories needs to be formalized. It has been demonstrated that certain topology concepts, such as 'interior', 'exterior' and 'neighbourhood' of a topological object, are appropriate for describing the global properties of vehicle and pedestrian trajectories (Papadimitriou, 2012). More specifically, the Jordan curve theorem of topology states that "a curve divides the plane space into two distinct sets, an 'interior' and an 'exterior' one and any path from one set to the other intersects with the curve". Considering the vehicle network as a Jordan curve, and that the 'interior' and 'exterior' parts of the curve's 'neighbourhood' correspond to the pedestrian walking network (i.e. sidewalks), it is possible to identify the number and location of potential pedestrian crossing points.

A next, more practical, step for the implementation of these concepts in a simulation framework would be the use of graph theory, with its concept of 'adjacency'. The main idea, here, is to split the networks in two, with one for the drivers and the second one for the pedestrians. The parametrization of the networks (links and nodes) allows for both the pedestrians and the drivers in their own networks to know the adjacent links of their own link, and by this way to perceive themselves and each other (Becarie et al. 2012).

Graph theory may provide a more useful representation of vehicle and pedestrian networks, given the consideration of 'nodes' and 'links', while the useful topological properties discussed above are maintained. An example of such a representation is shown in Figure 2.

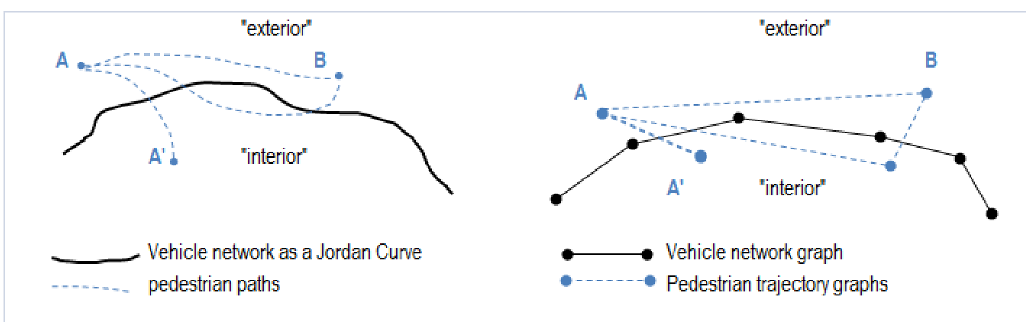

Figure 2 Topological representation of vehicle and pedestrian networks (left panel) and its extension to graph representation (right panel)

As regards the pedestrian route choice and wayfinding along a network, several researchers have recently demonstrated that pedestrians are expected to either minimize the number of changes in direction, or the total number of crossings (Vogt et al., 2012; Papadimitriou, 2012). Indeed, a path with several changes of direction (while staying 'along' the sidewalk) minimizes the number of crossings, especially of those outside junctions; on the other hand, a path that minimizes the changes of direction corresponds to an increased number of crossings, especially mid-block ones.

Integration of probabilistic models and simulation

Integration of models-driven rules in the simulation should be envisaged. In most microscopic models, rules are mostly derived from existing literature results or observational data. However, there is increasing evidence that pedestrian behaviour and choices are probabilistic, and the effects of the various determinants can be quantified in statistical analyses.
Schroeder and Rouphail (2011) demonstrate how empirical behavioural models of pedestrian gap acceptance and vehicle yielding behaviour can be used to improve the simulation of vehicle and pedestrian movement of mixed-priority areas, such as roundabouts. A similar earlier attempt was presented by Sun et al. (2003), where pedestrian gap acceptance and motorists yielding behaviour models were integrated in a simulation of uncontrolled mid-block crossings.
Several researchers stress that the results from observational studies and the resulting statistical models provide useful insight on specific behavioural elements of pedestrian movement, such as diagonal or mid-block crossing, which often contradict some popular rules used in pedestrian simulation. For example, Zhuang and Wu (2004) showed that, *"in the context of unmarked crossing, even with no constraints like green belts or there being no vehicles along the shortest path, pedestrians will not always take that shortest path"*. They further explain that, since vehicles are not static obstacles, but approach the crossing area with a certain speed and at a definite distance, pedestrians will make predictions of vehicle positions based on their estimated speed and distance to avoid potential collision and adapt their 'shortest path' accordingly.
Several studies show that, the route choice or the road crossing location choice may be affected (often dynamically) by the road environment and land use, the traffic conditions, the preferences of pedestrians (e.g. safety vs. delay acceptance), their age and gender etc. (Chu et al. 2004, Lassarre et al. 2007, Papadimitriou, 2012, Brémond et al. 2012).
The exploitation of probabilistic models in pedestrian simulation may lead to better exploitation of the advantages of both approaches (Papadimitriou et al., 2009).

CONCLUSIONS

The review of existing simulation models of pedestrian movement suggests that pedestrian simulation is a very popular research topic, examining important aspects of pedestrian behaviour and providing useful insights on pedestrian movement in various conditions. However, existing simulation tools focus on crowd, evacuation or route choice in an 'empty' network (i.e. without vehicle traffic). Moreover, the movement and behaviour of pedestrians is usually based on kinematic, traffic and utility equations, or on simple and often arbitrary rules – not always derived from actual observations. The different aspects and levels of pedestrian behaviour (i.e. route choice, road crossing choices, obstacle avoidance, interactions with vehicles or other pedestrians) are examined separately and not consistently, while their inter-relationships are not taken into account.
Therefore, three main challenges for the simulation of pedestrians and motorized traffic in urban areas were identified: first, the need to depart from and account for the hierarchical behavioural model of road users (strategic / tactical / operational behaviour); second, the need for appropriate description and parameterization of vehicle and pedestrian networks and their crossing points; third, the need to exploit in the simulation models the results of statistical and probabilistic models, which offer valuable insight in the determinants of pedestrian behaviour.
It is acknowledged that the simulation of pedestrians and motorized traffic involves methodological and practical difficulties possibly to a greater extent compared to the simulation of pedestrians alone. However, the new approaches for the management of urban systems, such

as the "safe systems" approach and the "shared space" concepts, bring forward the need to take into account the interactions between pedestrians and traffic within the system. Simulation models can provide useful and powerful tool to deal with these needs. Within this context, the simulation of pedestrians and motorized traffic should receive more attention in future research, in order to address the current difficulties and limitations, and eventually provide researchers and policy makers better tools to assess the mobility and safety implications of pedestrian movement in urban systems.

ACKNOWLEDGEMENTS

This paper is based on a research project implemented within the framework of the Action «Supporting Postdoctoral Researchers» of the Operational Program "Education and Lifelong Learning" (Action's Beneficiary: General Secretariat for Research and Technology), and is co-financed by the European Social Fund (ESF) and the Greek State.

REFERENCES

Airault V., Espié S., Lattaud C., and Auberlet J.M. (2004). Interaction between Pedestrians and their Environment when Road-crossing: a Behavioural Approach. In the Proceedings of the *24th Urban Data Management Symposium*, Fendel E. & Rumor M. eds., Italy, 2004.

Allen, T.M., Lunenfeld, H., and Alexander, G.J. (1971). Driver information needs. *Highway Research Record*, 366, pp. 102-l 15.

Antonini G., Bierlaire M., and Weber, M. (2006). Discrete choice models of pedestrian walking behavior. *Transportation Research Part B* 40, pp. 667–687.

Batty M., Jiang B. (1999). *Multi-agent simulation: New approaches to exploring space-time dynamics within GIS*. Centre for Advanced Spatial Analysis, Working Paper Series, Paper 10, University College London, 1999.

Becarie C. Bourgois L., Auberlet J.-M., and Leclercq L., (2012). Deliverable 32 of the French FUI 8 Project TERRADYNAMICA, 2012.

Bergman A., Olstam J., and Allström A. (2011). Analytical Traffic Models for Roundabouts with Pedestrian Crossings. *Procedia Social and Behavioral Sciences* 16, pp. 697-708.

Bierlaire, M., Antonini, G. and Weber, M. (2003). Behavioral dynamics for pedestrians, in K. Axhausen (ed) *Moving through nets: the physical and social dimensions of travel*, Elsevier.

Blue V.J., and Adler J.L. (2001). Cellular automata microsimulation for modeling bi-directional pedestrian walkways. *Transportation Research Part B* 35, pp. 293-312.

Borgers A. and Timmermans H. J. P. (1986). City centre entry points, store location patterns and pedestrian route choice behaviour: A microlevel simulation model. *Socio- Economic Planning Sciences* 20 (1), pp. 25-31.

Bourgois L., and Auberlet J.-M. (2012). Pedestrian Agent Based Model Suited to Heterogeneous Interactions Overseen by Perception. *6th International Conference on Pedestrian and Evacuation Dynamics*, Zurich, 6-8 juin 2012.

Brémond, R., Tom A., Désiré L., Gigout E., Granié M-A., and Auberlet J-M. (2012). Visual cues in pedestrian's crossing decision: in search of a quantitative model. In the Proceedings of the *91st Annual Meeting of the Transportation Research Board*, Washington DC.

Burstedde C., Klauck K., Schadschneider A., and Zittartz J. (2001). Simulation of pedestrian dynamics using a two-dimensional cellular automaton. *Physica A* 295, pp. 507–525.

Chu X., Guttenplan, M., and Baltes M. (2004). Why People Cross Where They Do - The Role of the Street Environment. *Transportation Research Record* No 1878, pp. 3-10.

Crooks A. Castle C., and Batty M. (2008). Key challenges in agent-based modelling for geo-spatial simulation. *Computers, Environment and Urban Systems* 32(6), pp. 417-430..

Daamen W., Hoogendoorn S.P., and Bovy P.H.L. (2005). First-order Pedestrian Traffic Flow Theory. *Transportation Research Record* 1934.

Dai J., Li X., and Liu L. (2013), Simulation of pedestrian counter flow through bottlenecks by using an agent-based model. *Physica A* 392, pp. 2202-2211.

Dijkstra J., and Timmermans H. (2002). Towards a multi-agent model for visualizing simulated user behavior to support the assessment of design performance. *Automation in Construction*, pp. 135–145.
Duives D.C., Daamen W., and Hoogendoorn S.P. (2013). State-of-the-art crowd motion simulation models. Article in press, *Transportation Research Part C*.
Feng S., Ding N., Chen T., and Zhang H. (2013). Simulation of pedestrian flow based on cellular automata: A case of pedestrian crossing street at section in China, *Physica A* 395 (13).
Gaud N., Galland S., Gechter F., Hilaire V., and Koukam A. (2008). Holonic multilevel simulation of complex systems: Application to real-time pedestrians simulation in virtual urban environment. *Simulation Modelling Practice and Theory* 16, pp. 1659-1676.
Gipps P.G. and Marksjö B. (1985). A micro-simulation model for pedestrian flows. *Mathematics and Computers in Simulation* 27, pp. 95-105.
Godara, A., Lassarre, S., and Banos, A. (2007). Simulating pedestrian-vehicle interactions in urban network using cellular automata and multi-agent models. In: *Proceedings Traffic & Granular Flow'05*, A. Schadschneider, T. Poschel, R. Kuhne, M. Schreckenberg, D.E. Wolf (Editors), Springer - Verlag.
Guo R-Y, Wong S.C., Huang H-J., Zhang P., and Lam W.H.K. (2010). A microscopic pedestrian-simulation model and its application to intersecting flows. *Physica A* 389 (2010), pp. 515-526.
Helbing, D., Buzna, L., Johansson, A., Werner, T. (2005). Self-organized pedestrian crowd dynamics: Experiments, simulations, and design solutions. *Transportation Science* 39 (1), pp. 1-24.
Helbing, D., Molnár, P. (1995). Social force model for pedestrian dynamics. *Physical Review* E 51 (5), pp. 4282-4286
Hoogendoorn S.P. (2004). Pedestrian flow modeling by adaptive control. *Transportation Research Record* 1878.
Hoogendoorn S.P., and Bovy P.H.L. (2004). Pedestrian route-choice and activity scheduling theory and models. *Transportation Research Part B* 38, pp. 169–190.
Huang L., Wong S.C. Zhang M., Shu C-W., and Lam W.H.K. (2009). Revisiting Hughes' dynamic continuum model for pedestrian flow and the development of an efficient solution algorithm. *Transportation Research Part B* 43, pp. 127-141.
Hughes, R.L. (2002). A continuum theory for the flow of pedestrians. *Transportation Research Part B* 36, pp. 507–535.
Hunt, J., and Griffiths, J. (1991). *Pedestrian Crossing Criteria Research: Random Crossing Model*. TRL Contract Report CR248, Transportation and Road Research Laboratory, Crowthorne, UK, 1991.
Ishaque M.M., and Noland R.B. (2008). Behavioural Issues in Pedestrian Speed Choice and Street Crossing Behaviour: A Review. *Transport Reviews*, pp. 1-25.
Jiang Y., Wong S.C., Zhang P., Liu R., Duan Y., and Choi K. (2012), Numerical simulation of a continuum model for bi-directional pedestrian flow, *Applied Mathematics and Computation* 218, pp. 6135-6143.
Kitazawa, K., and Batty, M. (2004). Pedestrian Behaviour Modelling: An Application to Retail Movements using a Genetic Algorithm. *7th International Conference on Design and Decision Support Systems in Architecture and Urban Planning*.
Kukla R., Kerridge J., Willis A., and Hine J. (2001). PEDFLOW: Development of an Autonomous Agent Model of Pedestrian Flow. *Transportation Research Record* No 1774, pp. 11-17.
Lassarre S., Papadimitriou E., Yannis G. and Golias J., (2007). Measuring accident risk exposure for pedestrians in different micro-environments. *Accident Analysis and Prevention* 39 (6), pp. 1226-1238.
Lee J.Y.S, and Lam W.H.K. (2008). Simulating pedestrian movements at signalized crosswalks in Hong Kong. *Transportation Research Part A* 42, pp. 1314-1325.
Li, Y., and Tsukaguchi, H. (2005). Relationships between network topology and pedestrian route choice behavior. *Journal of the Eastern Asia Society for Transportation Studies* 6, pp. 241 - 248.
Liu R., Cruz da Silva J.P., and da Maia Seco A. J. (2000). A bi-modal microsimulation tool for the assessment of pedestrian delays and traffic management. In the Proceedings of the *9th International Association of Travel Behaviour Research Conference*, Gold Coast, Australia, 2000
López-Neri E., Ramírez-Treviño A., and López-Mellado E. (2010). A modeling framework for urban traffic systems microscopic simulation. *Simulation Modelling Practice and Theory* 18, pp. 1145-1161.
Løvås G.G. (1994). Modeling and simulation of pedestrian traffic flow. *Transportation Research Part B* 28 (6), pp. 429-443.
Mitchell D. H., and MacGregor Smith J. (2001). Topological network design of pedestrian networks. *Transportation Research Part B* 35, pp. 107-135.
Osaragi, T. (2004). Modeling of Pedestrian Behavior and Its Applications to Spatial Evaluation. Proceedings of the *Third International Joint Conference on Autonomous Agents and Multiagent Systems*, 2004.

Papadimitriou E. (2012). Theory and models of pedestrian crossing behaviour along urban trips. *Transportation Research Part F* 15 (1) , pp. 75-94.
Papadimitriou E., Yannis G., and Golias J. (2009). A critical assessment of pedestrian behaviour models. *Transportation Research Part F* 12 (3), pp. 242-255.
Schroeder B.J., and Rouphail N.M. (2011). Empirical Behavioral Models to Support Alternative Tools for the Analysis of Mixed-Priority Pedestrian-Vehicle Interaction in a Highway Capacity Context. *Procedia Social and Behavioral Sciences* 16, pp. 653-663.
Sun D., Ukkusuri S.V.S.K., Benekohal R.F., and Waller S.T. (2003). Modeling of Motorist-Pedestrian Interaction at Uncontrolled Mid-block Crosswalks. In the Proceedings of the *82nd Annual Meeting of the Transportation Research Board*, Washington DC.
Te Velde A.F, van der Kamp J., Barela J.A., and Savelsbergh G.J.P (2005). Visual timing and adaptive behavior in a road-crossing simulation study. *Accident Analysis and Prevention* 37, pp. 399–406.
Teknomo K. (2006). Application of microscopic pedestrian simulation model. *Transportation Research Part F* 9, pp. 15–27.
Timmermans H., Van Der Hagen X., and Borgers A. (1992). Transportation systems, retail environments and pedestrian trip chaining behaviour: Modelling issues and applications. *Transportation Research Part B* 26B (1), pp.45-59.
Torrens P.M., Nara A., Li X., Zhu H., Griffin W.A., and Brown S.B. (2012). An extensible simulation environment and movement metrics for testing walking behavior in agent-based models. *Computers, Environment and Urban Systems* 36, pp. 1-17.
Usher J.M., and Strawderman L. (2010). Simulating operational behaviors of pedestrian navigation. *Computers & Industrial Engineering* 59, pp. 736-747.
Van Der Molen H., and Bötticher A (1988). A hierarchical risk model for traffic participants. *Ergonomics*, 31(4), pp. 537-555.
Vogt R., Nikolaidis I., and Gburzynski P. (2012). A realistic outdoor urban pedestrian mobility model. *Simulation Modelling Practice and Theory* 26, pp. 113-134.
Wakim C.F., Capperon S., and Oksman J. (2004). A Markovian model of pedestrian behavior. In the Proceedings of the *2004 IEEE lntenational Conference on Systems, Man and Cybernetics*, pp. 4028-4033.
Weifeng F., Lizhong Y., and Weicheng F. (2003). Simulation of bi-direction pedestrian movement using a cellular automata model. *Physica A* 321, pp. 633 – 640.
Xi H., and Son Y-J. (2012). Two-level modeling framework for pedestrian route choice and walking behaviors. *Simulation Modelling Practice and Theory* 22, pp. 28-46.
Yang J., Deng W., Wang J., Li Q., and Wang Z. (2006). Modeling pedestrians' road crossing behavior in traffic system micro-simulation in China. *Transportation Research Part A* 40, pp. 280–290.
Yue H., Guan H., Zhang J., and Shao C. (2010), Study on bi-direction pedestrian flow using cellular automata simulation, *Physica A* 389 (2010), pp. 527-539.
Zhuang X. and Wu C. (2011), Pedestrians' crossing behaviors and safety at unmarked roadway in China. *Accident Analysis and Prevention* 43, pp. 1927-1936.