GEOSIMULATION, AUTOMATA, AND TRAFFIC MODELING*

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INTRODUCTION

Recent developments in the research landscape have made possible a new paradigm for spatial simulation, what is coming to be known in the geographical sciences as the *geosimulation* approach. This novel approach to simulation development is characterized by detailed, dynamic, and interactive simulation environments, often operating in near-real-time and exhibiting very realistic characteristics. A new class of "microscopic" simulation has begun to emerge around the approach, focused on automata-based tools for model-building (Torrens 2002). This chapter discusses the potential of geosimulation for traffic modeling and describes how geosimulation-style tools—cellular automata and multi-agent systems—have been used to build a variety of vehicle and pedestrian traffic simulations. The chapter also explores some of the current limitations of the field, particularly as an applied science, and discusses future avenues of potential research inquiry.

RECENT DEVELOPMENTS IN THE RESEARCH LANDSCAPE

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The emergence of a new class of simulation tools for traffic modeling has been catalyzed by recent developments in several fields, including computer hardware, computer science, "dataware", and complexity studies.

The computer hardware now available for running transport simulations is unprecedented when compared with that which was available only a few years ago. Advances in central processing units (CPUs), graphics processing units (GPUs), data storage, bandwidth, and parallel computing have made possible the construction of highly detailed and dynamic simulation environments for studying traffic, and in many cases these models can be run from desktop machines.

In parallel, important advances in computer science have influenced traffic simulation, either by providing new programming environments for developing simulation software or by introducing new methodologies for formulating traffic models. Object-oriented (OO) programming languages—Java and C# are popular examples—have been particularly influential. They have provided a new knowledge representation paradigm for applied science (Gimblett 2002). The OO approach is particularly useful for simulation because it provides an intuitive framework for binding entities (objects) and the behavior (methods) that governs their interactions. Other developments in computer science, such as Artificial Intelligence (Kurzweil 1990, Kurzweil 1999) and Artificial Life (Levy 1992), have also been influential, particularly in introducing new simulation techniques. Artificial neural networks (Gurney 1997) have been particularly influential, as have been methodologies borrowed from intelligent agents research (Schleiffer 2002). Automata-based tools (Sipper 1997) have been especially significant; they form the basis for geosimulation-style tools in most of the examples that will be discussed in this chapter.

In many instances, recent advances in transport simulation have been supported by developments in the "dataware" used to support modeling. Advances in Geographic Information Science have provided Geographic Information Systems for storing, manipulating, and visualizing spatial data used in building models, and spatial analysis has provided new methodologies for processing that data. A new field, Geographic Information Systems for Transportation (GIS-T), has emerged in recent years (Miller and Shaw 2001, Thill 2000). Advances in photogrammetric and geomatic engineering have also provided new, remotely sensed, data sources for transport models.

Transport model developers are also finding new ways to interpret—and model—transport systems as complex adaptive systems, using ideas from complexity studies. The idea of *emergence* (Holland 1998), which characterizes systems as the product of bottom-up and local scale *interactions* between independent components, has been widely adopted. This replaces reductionist approaches, which treat systems as simple top-down aggregations of system parts.

Ultimately, these developments have had important implications for the ways in which we now model transport systems. New opportunities for developing models with hitherto unseen degrees of realism are now available. In particular, these developments have facilitated advances in the representation of dynamics, scale, interaction, and entities in transport models, broadening the range of systems that modelers can now simulate, as well as revitalizing the ways in which we consider simulation as an exercise.

THE EMERGING GEOSIMULATION APPROACH

Geosimulation is a catch-all phrase that can be used to represent a "new wave" of simulation that has come to prominence in recent years. The geosimulation approach builds on advances that have been discussed above, drawing together a diversity of theories and techniques across disciplinary boundaries, offering unique and innovative perspectives on spatial simulation. The approach is used most prominently in urban simulation, and has also been widely used to build traffic models.

Geosimulation-style traffic models have a number of innovative characteristics that distinguish them from "traditional" approaches, and these attributes draw, in most cases, directly from the advances that were discussed in the last section.

The first distinguishing aspect relates to the depiction of *time*. In many cases, traffic models designed in the geosimulation framework operate in near-real-time, with time divided into discrete "packets of change" (Anderson 2002) that approximate the reaction time of drivers or pedestrians. Geosimulation-style traffic models are often dynamic in other senses, with simulated entities reacting to evolving traffic conditions, as they occur in the simulation.

The second aspect is associated with the representation of *scale*. Traditionally, traffic models have been designed to operate at relatively coarse spatial scales, such as the Traffic Analysis Zone (TAZ), and, arguably, the results that they generate are of relatively little value because of the scales at which they operate (Batty 2001). For example, standard land-use and transport models commonly ignore pedestrian traffic, in many instances because the available methodologies cannot adequately represent trips at that scale. However, the advances that we have already discussed have made the design of very detailed simulations possible, commonly at "microscopic" scales at the level of individual vehicles and pedestrians.

The third distinguishing factor, the ability to perform *entity-based* simulation (Benenson and Torrens 2003), is closely related to this. The increase in resolution of traffic simulation has made it possible to abandon the idea of a "mean individual", with average behaviors and characteristics derived from those of the group. Simulated entities can be designed, instead, at an "atomic" level (Anderson 2002), with entities represented in terms of their *distinct* individual attributes and behavior (Gimblett 2002). This has important implications for circumnavigating problems of ecological fallacy in model development, because the models can be run with spatially non-modifiable units.

The fourth characteristic is *interaction* and its representation. It is now possible to move beyond a reliance on interaction as flows between modeled entities—an approach characterized by gravity and spatial interaction models—and into the representation of more *localized* interaction. Higher-level interactions can also be represented, often seamlessly, as they emerge from more micro-scale activity. In addition, the geosimulation approach allows model developers to abandon the notion that interactions take place evenly across a system (Anderson 2002).

Fundamentally, this has resulted in a paradigm shift in traffic simulation. There is now a sense of using geosimulation-style environments as tools for hypothesis testing and "what-if" scenario exploration, but with an unprecedented degree of realism.

AUTOMATA AS GEOSIMULATION TOOLS

The geosimulation approach is perhaps best represented in *automata*-based modeling. Automata-based tools such as cellular automata (CA) and multi-agent systems (MAS) encapsulate all of the features of the geosimulation approach described in the previous sections. Both tools are used to develop geosimulation-style traffic models.

Automata are general processing units, most often artificial in design. They can be endowed with characteristics that change over time based on the internal attributes of the automaton itself, a set of transition rules, and input from outside the automaton. Automata provide a formal mechanism for expressing the fundamental elements of a system and the nature of their interactions. Mathematically, an automaton can be described with a few symbols:

$$S_{t+1} = f\,(S_t, I_t)$$

States (S) describe the attributes of an automaton at a given point in time *(t)*. *Transition rules,* expressed here as a functional statement *(f)*, govern how the state of an automaton should change from time *t* to a subsequent period in time *(t + 1)*. The transition calculation is based on the state of the automaton itself at time *t*, as well as information gleaned from an input *(I)* of some description, usually derived from the states of neighboring automata, introduced at time *t*.

CA and MAS are extensions of this basic idea. In CA, individual automata are interpreted as being housed within a cellular boundary, such as a grid square. Together, these *"cells"* form a continuous *lattice* of connected automata, and individual automata are fixed in this lattice. External input to particular automata is derived from a *neighborhood* of cells within a localized area of the lattice around an automaton (Figure 1). With MAS, individual automata are themselves free to move in space; they are mobile (Figure 2). Furthermore, the attributes that describe individual automata generally attribute some agent-like qualities to the unit, such as anthropomorphic characteristics, and the transition rules that govern change in MAS are usually interpreted to represent agent-like behaviors, such as preference formulation, walking movement, driving behavior, etc.

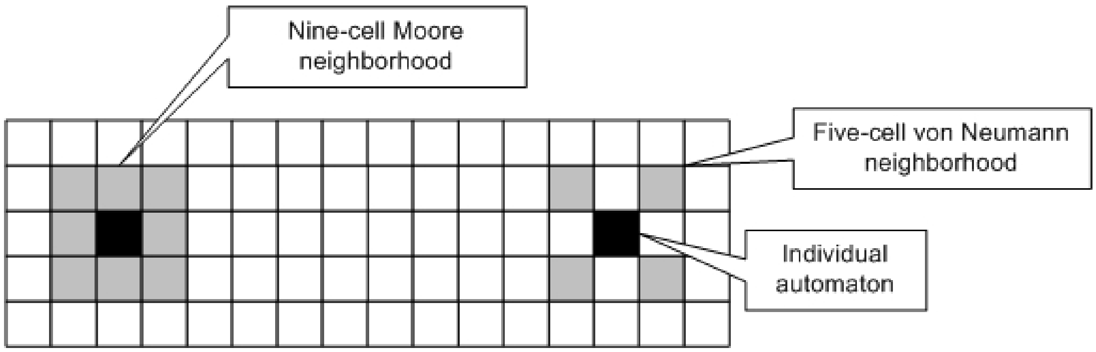

Figure 1. Cellular automata.

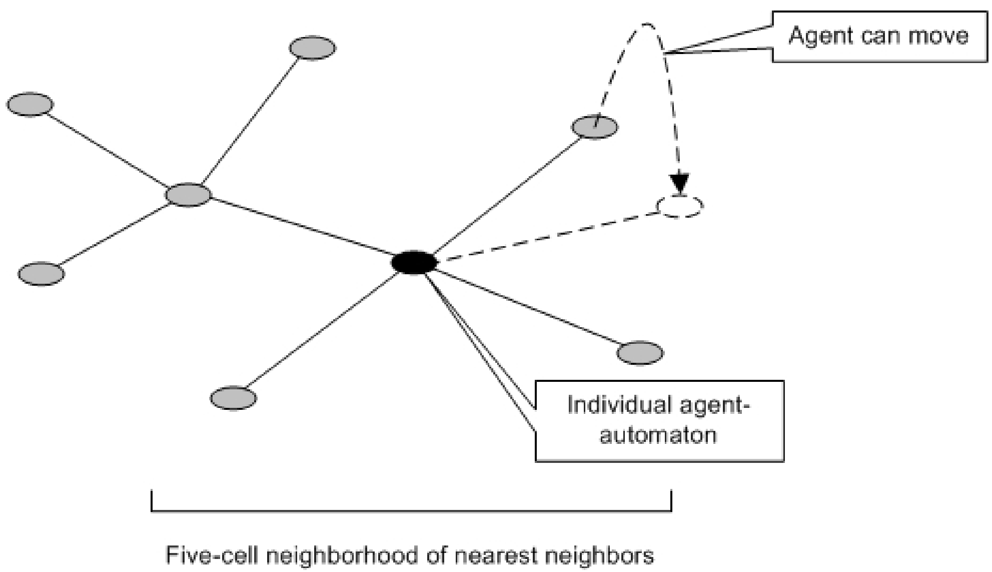

Figure 2. Multi-agent systems.

Automata-based tools such as CA and MAS encapsulate all of the features of the geosimulation approach and provide a methodology for representing them in a simulation framework. Time is handled through the transition function, which determines how automata states change dynamically. A variety of scales can be accommodated, since automata can be designed to represent units of any desired resolution. The entity approach is facilitated through the independent and discrete specification of individual automata. Finally, interaction is enabled through the neighborhood function, which determines how independent automata units should react to, and interact with, neighboring units.

Hopefully, it is easy to envisage how various traffic systems can be represented as interacting collections of automata. Automata can be designed to represent any unit of a traffic system: vehicles, pedestrians, sections of sidewalks, etc. These entities can be endowed with various attributes of relevance to traffic: velocity, demographic characteristics, speed limits, etc. Automata might be associated with various lattices, designed to represent features of a transport system: regular grid-based tessellations, irregular grids, graph-based networks of nodes and edges, etc. Also, neighborhood functions can be used to mimic features of traffic systems, such as gaps between vehicles, spaces for overtaking in adjacent lanes, pedestrians' perception of the space immediately surrounding them, etc. Transition rules can be designed to represent an almost limitless array of behaviors and processes: lane-changing rules, rules describing motion, collision avoidance, etc. In addition, a variety of time scales can be introduced into the models.

In the sections that follow, we will outline the use of geosimulation-style automata tools to model vehicular and pedestrian traffic systems. The various ways in which spatial topology, entity descriptions, neighborhood definitions, time, and transition rules are encoded into the models will be discussed.

MODELING VEHICULAR TRAFFIC

The geosimulation approach allows for "microscopic" traffic modeling, with individual vehicles being simulated as independent entities, and permits for the simulation of interactions between those vehicles along simulated roads. Often, recognizable traffic conditions, such as congestion (Nagel and Schrekenberg 1995), emerge from these interactions and in many cases the models provide mechanisms for simulated entities to react and adapt to these conditions as they evolve in near real-time.

Automata-based traffic models are developed in much the same way as those described in the previous sections. The spatial or network structure of the traffic environments that are being simulated are encoded into the model as lattices. Simulated entities are designed with various characteristics that enable them to function in a manner similar to their real world counterparts. Neighborhoods of influence designate the spatial domain of interactions between entities in the simulation. Some form of internal clock is introduced into the simulation, allowing for dynamic action in the model. Conditional rules and calculations are also included in the simulation, describing how modeled entities should perceive their modeled environment, react to changes in their own state descriptions, react to other entities in the simulation, and react to changes in their environment. Automata, either CA or MAS, are the principal mechanism used for the simulation of vehicles and the environment in which they travel.

Spatial topology

Roads are encoded into automata models in familiar ways: lattice nodes represent road junctions and links represent roads that connect those junctions. Additional detailed topology may also be introduced. In the

TRANSIMS model, for example, land-use and connectivity data, intersections (signs and signals), activity locations, parking, transit stops, and route paths are also encoded into the topology of the model (Barrett, et al. 1999).

Queues are used to represent the vehicles that travel along a link. Queues are commonly encoded as one-dimensional lattices (or parallel lattices where multi-lane roads are represented), with each cell in the lattice represented as a cellular automaton. Where models are developed for experimental purposes, such as studying the formation of congestion in an abstract sense, queues may be coded with periodic boundary conditions, i.e., traffic moves in a continuous loop through the queue (Rickert, et al. 1996). Various characteristics can be associated with the cells that form a queue, e.g., length, flow capacity, free flow velocity, free flow travel time, etc. (Cetin, et al. 2001). In this way, automata cells and lattices can be used to build realistic traffic environments.

Entity descriptions

One of the great advantages of the geosimulation approach is that it allows simulated entities to be represented as atomic objects. Whereas spatial interaction models represent aggregate flows of traffic, geosimulation models represent the individual particles that comprise that flow: individual cars and trucks and their drivers for vehicular traffic, and individual walkers for pedestrian traffic. In most of the microscopic traffic models, vehicles are encoded as individual cells of 7.5 meters in length, which is the length of a car plus the gap between cars in a jam (Wagner, et al. 1997).

Simulated entities can be afforded a rich range of state descriptors describing their characteristics. There is no need for “mean individual” descriptions; entities can be represented as true individuals. In the PARAMICS model, for example, individual vehicles are encoded with state variables that represent a vehicle’s length, maximum acceleration and deceleration, cornering speed, desired destination, preferred traveling speed, current position, and current direction (Wylie, et al. 1993). The TRANSIMS model is also capable of representing much of that information but adds even more detail to the description of vehicles, including a record of the household to which the vehicle belongs, the initial network location of the vehicle, and a vehicle classification from a 23 type scheme (Barrett, et al. 1999).

Neighborhood definitions

Neighborhoods of influence can be defined for individual vehicle-automata in the simulation. These neighborhoods represent the range of influence for interaction between modeled entities. Neighborhoods are used to model drivers' "perception" of traffic conditions around them, such as the buffer between adjacent cars in the same lane, or gap opportunities for merging traffic at junctions (Wylie, et al. 1993). Sophisticated neighborhood functions may also be introduced to facilitate lane-changing decisions, for example, how far to look ahead or behind in the same lane and how far to look ahead in adjacent lanes before switching position (Rickert, et al. 1996). Neighborhoods can be defined in static terms, e.g., occupancy of five cells ahead or in front of a vehicle (Barrett, et al. 1999). Or, alternatively, neighborhoods can be related to other dynamic characteristics of the model, such as the velocity of a moving vehicle (Rickert, et al. 1996).

Time

The ability to encode dynamic relations in a simulation model is another advantage of the geosimulation approach for traffic modeling, where users are often interested in moment-by-moment traffic dynamics for systems of interest. There are two ways in which the geosimulation approach is particularly innovative in relation to its treatment of time: temporal resolution and parallel update. Traffic applications of geosimulation-style modeling are among some of the most fine-scaled simulations, in terms of temporal resolution, in urban studies. This is partly because they need to be—the reaction time of drivers is on the order of one second (Wagner, et al. 1997)—and is partly a function of the incredible computing power available to compile and run these models. Further advantages stem from the synchronous nature of transition rules in the models. In keeping with automata-based principles, traffic geosimulation models are often updated in *parallel* (on supercomputers, clustered processors, or networks of machines); transition rules are applied to modeled entities and their states are altered in unison, throughout the simulation. When coupled with a fine-scale temporal resolution, this enables the simulated system to "evolve" dynamically analogous to real world conditions. In this sense, traffic geosimulation models can now be run, in many cases, in near-real-time for medium size cities. In addition, the reaction of individual vehicles to *evolving* traffic conditions (accidents, congestion, detours) can be simulated dynamically.

Rules

Various transition rules can be used to characterize the behavior of vehicles, and their drivers, in automata-based traffic simulations. Of course, it would be a daunting task to formulate rules to mimic the full range of driving behaviors, so model developers focus on a minimal set of rules instead (Wagner, et al. 1997). Just as in complexity studies, traffic simulations are designed with a few simple rules and it is hoped that more complex behaviors will "emerge" through the myriad application of those rules between many interacting entities.

Traffic geosimulation models are noteworthy in their attention to rules of *movement*. Transition rules are formulated to simulate acceleration and braking as a function of various vehicle characteristics (speed, maximum velocity, target speed) and conditions in a vehicle's neighborhood (type of road, perceived traffic conditions ahead, gap to the next car) (Wagner, et al. 1997, Wylie, et al. 1993). In some instances, random acceleration and deceleration functions are also introduced to mimic erratic movement (Rickert, et al. 1996). Rules for collision-avoidance have also been introduced. Other rules have been developed to simulate signal stopping behavior (Barrett, et al. 1999) and traffic movement at junctions, with "gap acceptance" functions that determine how long vehicles must wait at a junction before they can proceed (Wylie, et al. 1993). In models where collections of vehicles are simulated as traffic queues (Barrett, et al. 1999, Cetin, et al. 2001, Rickert, et al. 1996), entrance and departure from vehicle queues can also be simulated, with vehicles leaving a queue freeing up space on a link, allowing another vehicle to join the queue.

Quite elaborate rules have also been devised to simulate lane-changing behavior. In this sense, automata models resemble traditional queuing lane models. However, traditional queuing lane models are not truly multi-lane in their design (Cetin, et al. 2001); they *approximate* multiple lanes by switching the positional order of vehicles to make it appear as if passing has occurred. In automata models, however, parallel lattices can be constructed adjacent to each other, facilitating the simulation of movement between lanes. Lane-changing rules in automata traffic models can the simulate exchanges of vehicles between lanes as a function of a variety of factors, including the number of empty sites in a vehicle's neighborhood ahead in the same lane, ahead in adjacent lanes, and behind in adjacent lanes; velocity; and hindrance in the current lane (Rickert, et al. 1996, Wagner, et al. 1997).

MODELING PEDESTRIAN TRAFFIC

Traditionally, pedestrian traffic has been comparatively ignored by transport modelers. There are many reasons why this may have been the case (Batty 2001). To a certain degree, pedestrian traffic has been overshadowed by vehicular traffic as an area of applied research. The demand for vehicular transport, at least in contemporary metropolitan areas in developed countries, out-paces that for pedestrian modes of travel by a significant margin. Likewise, the multitude of problems—environmental, health, social justice—associated with vehicular transport overshadows those ties to pedestrian travel. Scale issues also factor into the relative favor afforded vehicular transport. The range of movement permitted by vehicular transport, and the associated scale of its influence, are far greater than that of pedestrian movement. Vehicular transport problems are also, to some extent, more "tractable" than pedestrian transport problems (Batty 2001), partly because of the aforementioned scaling issues, and partly because of the greater attention paid to vehicles and the wider array of modeling techniques that are available.

However, in recent years, the landscape for pedestrian transport research has improved considerably. This is partly a response to shifts in the political agenda in relation to transport, particularly heightened awareness of "sustainability" in urban environments and modes of transport. As in other area of transport modeling, the field has also benefited from innovations in the research landscape. The development of geosimulation-style approaches, however, has perhaps been most significant in initiating the recent flurry of research in pedestrian modeling. This has been supported by the development of new data capture techniques for pedestrian models: aerial photography for capturing crowd volumes and movement through automated observation, time lapse filming, video data, and intelligent image processing techniques for extracting information from these data.

Together, these advances have enabled the development of innovative, microscopic, “agent-based” pedestrian simulations in which the activity schedules and second-by-second movement and interactions of individual walkers are simulated, sometimes for large crowds of pedestrians in whole districts of a city. These models enable applied work to be performed that had either been previously intractable or not imagined at all.

Pedestrian traffic modeling is, in many respects, a far more complex simulation problem than vehicle traffic modeling. This is particularly true at “microscopic” levels. The scale of observation can often be much finer for pedestrian modeling, simply because the “footprint” of a pedestrian is generally much smaller than that of a vehicle. Furthermore, the behavior of pedestrians is not as constrained as that of vehicles on roads. There are generally many more paths available to pedestrians when compared to vehicles. Pedestrians are also much less limited in their range of movement; they can, for example, perform side-step and about-face maneuvers. Pedestrians are not generally constrained by rules of the road; they can, for example, ignore crossing rules at intersections by jaywalking. Finally, pedestrians themselves, as well as their behavior, are much more varied than vehicles, at least in a general sense. Despite the age, gender, social, cultural, and health characteristics of various drivers, most cars behave in a relatively similar manner on the road. That is not true of pedestrian walkers.

For these reasons, geosimulation-style techniques are ideally suited to modeling pedestrian traffic. MAS, in particular, are well-suited to the task. The comparative flexibility of MAS tools compared to CA, with respect to representing movement and interaction, makes them ideal for representing complex adaptive phenomena like pedestrian crowds.

Entities

Generally, geosimulation-style pedestrian traffic models provide for the representation of two types of entities: agent-pedestrians and pedestrian obstacles in the built environment. The simulated vehicle drivers discussed in the previous section could have various demographic and socioeconomic state variables associated with them. This is also the case with pedestrian traffic models, where simulated agent-pedestrians are often attributed various life-like characteristics to help shape their movement behavior and to populate the models with agents that are likely to behave in a diverse fashion (Haklay, et al. 2001). Other characteristics of relevance to traffic modeling can be observed as agents move within the simulation, e.g., position, direction, time in the system, movement, states, etc., and this has close analogies with other pedestrian flow modeling approaches (Hoogendorn and Bovy 2002).

State variables can also be ascribed to various entities used to represent the physical environment in which pedestrian agents interact, both in terms of attraction features (buildings, shops, etc.) and potential obstacles (street furniture, walls, road signs, etc.) (Kerridge, et al. 2001).

Spatial topology

Invariably, grid-based lattices are used to represent the spatial topology of the environments in which agents interact, as is the case in vehicle traffic models. Of course, a finer resolution of representation is often necessary for pedestrian models; in some instances grid squares have been used to represent spaces of 750mm in size. Various features of the built environment—building outlines, land-uses, divisions between sidewalks and roads, network data, gateways and waypoints, etc.—may be embedded into this typology, either as raster or vector data. Also, various representations of street and building layouts can be altered in the model structure to allow for the evaluation of planning and design issues relating to pedestrian movement.

Time

As in most geosimulation-style models, time is generally discrete in pedestrian traffic simulations, proceeding in "chunks" that approach real-time. However, discrete units of time are commonly designed at very fine temporal scales. In the PEDFLOW model (Kerridge, et al. 2001), for example, time is divided into slots of one tenth of a second in duration.

Neighborhoods

Various neighborhood functions may be introduced to determine pedestrian agents' "awareness" of conditions in the environments surrounding them, both for the detection of targets and potential obstacles and the determination of avenues for collision avoidance. In their models of agent-based shoppers, (Turner and Penn 2002), specify agents with neighborhoods derived from their lines-of-sight. In the STREETS model (Haklay, et al. 2001), agents "look" in up to five directions in their immediate vicinity to determine where the most space is available for movement. In the PEDFLOW model (Kerridge, et al. 2001), agents are equipped with three neighborhood filters: a "static awareness" function that determines how far ahead an agent can "see"; a "preferred gap size" that governs the smallest space a pedestrian is willing to move into;

and a "personal space" function that sets the amount of buffering space a pedestrian would like to maintain around itself. These neighborhood functions provide simulated pedestrians with the spatial "cognition" necessary for realistic movement patterns.

Rules

It has been noted that, as is the case with vehicular traffic movement, there is an almost limitless array of behaviors and factors that contribute to the movement dynamics of a pedestrian crowd. Nevertheless, pedestrian movement is surprisingly predictable. Despite the apparent chaos of crowd dynamics, certain regularities can be observed and these can be used to formulate transition rules to drive movement behavior in agent-based simulations. Papers by Helbing and colleagues (Helbing, et al. 2000, Helbing, et al. 2001) detail several of these regularities. Pedestrians usually pursue the fastest route to a target destination and prefer to travel at the most comfortable walking speed. Pedestrians also like to maintain a buffering distance from other pedestrians and obstacles. Certain automatic behaviors may also be observed in certain situations, e.g., when entering congested doorways or side-stepping obstacles. Also, at a more macro-level, gas- or fluid-like qualities may be attributed to pedestrian crowds at certain densities, and similarities with granular flows have also been noted. These observations may be used to formulate transition rules governing the speed and movement of pedestrian agents in traffic simulations.

In the PEDFLOW model (Kerridge, et al. 2001), for example, the speed of pedestrian agent movement is determined by factoring in the time period over which an agent occupies a grid square, proportional to its own walking speed or that of other pedestrian agents in its neighborhood. In the STREETS model (Haklay, et al. 2001), pedestrian agents are endowed with maximum walking speed attributes and categorical variables that characterize their speed at any given moment (e.g., "stuck", "standing", "moving") and these variables are used to determine the speed at which a simulated pedestrian walks.

Agent movement—way-finding and navigation—is determined by rules that are analogous to those for vehicular traffic. Activity models determine the overall movement schedules of agents and any associated target destination or waypoints. (Agents may decide to adhere to those schedules or wander from pre-assigned targets.) Various navigation rules then determine how agents navigate to those destinations within their simulated environments, reacting to and interacting with the emerging dynamics within the simulated system. In the STREETS model (Haklay, et al. 2001), for example, various "helmsman" rules are used to mediate between an agent's "best heading" and its desired target, while "navigator" rules maintain agents' overall heading in relation to targets. On a more micro-scale, rules are often introduced to determine how pedestrian agents should react to evolving conditions in their immediate surroundings: to determine step-by-step movement and collision detection. In the STREETS model, a "walkability" calculation is performed to assess whether enough space exists ahead of an agent for it to proceed along its route. Agents then move to grid squares with the most "walkability". In the PEDFLOW model (Kerridge, et al. 2001), agents perform similar calculations in relation to their neighborhoods, distinguishing between observed entities in that neighborhood (other pedestrian agents, goal points, stationary obstacles, buildings, and kerbs). Agents calculate the distance to those objects and then execute one of four actions to proceed: go straight ahead, go diagonally left or right, move to the side (a choice parameter determines which side they favor), or remain where they are. Using these rules, pedestrian agents can be designed, choreographically, to mimic the movement patterns of real walkers, both at an individual scale and as a crowd.

EPILOG

We have just described how automata-based tools can be used, as geosimulation-style models, to simulate detailed and dynamic interactions in vehicular and pedestrian traffic systems. The limitations associated with these tools in urban simulation have been addressed elsewhere (Batty and Torrens 2001, Torrens and O'Sullivan 2001). While the introduction of these tools to traffic simulation has several advantages and offers much potential for the development of more realistic and useful traffic simulation environments, a number of hurdles to their widespread deployment remain.

Existing theory about traffic systems may be inadequate for developing geosimulation-style traffic models. In particular, further development may require new understandings of interactive traffic behavior, in particular of how it organizes from micro- to macro-scales. This is particularly true in relation to pedestrian modeling, which, as we have seen, has not been as actively pursued as vehicle traffic modeling. Nevertheless, significant new insights are being made, particularly in relation to observed regularities in pedestrian movement patterns (Helbing, et al. 2000, Helbing, et al. 2001) and pedestrian choice heuristics (Kurose, et al. 2001). Geosimulation tools may well play a role in exploring and validating new theories.

Because of their fine resolution and dynamic nature, geosimulation models often require large amounts of computing resources to run. Despite recent developments in computer hardware, the volume of entities and interactions represented in geosimulation-style models makes them extremely “resource hungry” in terms of computing power. Processing power, in particular, is still weak in many instances. Advances in the processing power of traffic simulations is being made, particularly in relation to networking computers and harnessing their combined processing power (Nagel and Rickert 2001), but research into this field is likely to continue.

Other issues remain regarding the application of geosimulation-style models in practice. To a certain extent, many of these simulations, particularly those developed for pedestrian traffic, are academic in nature. Despite popular applications to case studies (Barrett, et al. 2001), the tools have yet to enjoy widespread testing in real-world contexts.

Data considerations are also important. In some instances, detailed data sets exist to “feed” geosimulation-style models, but generally fine-scale data are not readily available. This makes the validation and calibration of geosimulation-style models a difficult task. It is likely that new data sources will become available, but in the meantime, research is uncovering innovative approaches to the dataware problem. The generation of data sets containing "synthetic" households and vehicles (Bush 2001) is one such avenue of research inquiry.

Nevertheless, despite these caveats, the geosimulation approach offers promising avenues for traffic model development. The introduction of automata-based tools, in particular, to traffic simulation, has enabled the construction of a new class of simulation. These environments enable the incorporation of a diversity of theoretical ideas about traffic systems directly into the simulation framework, and facilitate the development of richly detailed and dynamic simulation environments. The field is in its early stages of exploration, but the indications for the development of innovative tools, testing of new theories, and application of simulation to applied contexts look promising.

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