CO-289

AGENT-BASED MODELING OF EMERGENCY EVACUATION IN A SPATIALLY-AWARE AND TIME-AWARE ENVIRONMENT

CHEN X.
Northern Illinois University, DEKALB, UNITED STATES

1. BACKGROUND AND OBJECTIVES

This study aims to create a fundamental framework and build a prototype model for spatially-aware agent-based models with time-aware Geographic Information System (GIS) for emergency evacuations. It attempts to address two critical issues in coupling agent-based modeling with GIS: implementing spatial awareness of agents in geographic space and integrating the dynamics of the environment and its impacts on the behavior of agents.

Agent-based model (ABM) has advantages in capturing emerging behavior resulting from interactions between individuals in a complex system. In ABM, agents are intelligent individuals who make decisions based upon the interactions with other agents and the environment in which they are situated. Spatial awareness is a critical feature of ABM. It emphasizes the capability of agents to detect the properties of their environment and adapt their behavior to the changes in the environment.

Time-aware GIS refers to a system that can present and update the dynamics of the geographic space or the environment of the agents. The environment in ABM can be either static or dynamic. In most emergency situations (wildfires, weather events such as hurricanes and blizzards, floods, hazmat situations, etc.), however, a static environment represents not only an oversimplification, but an unrealistic assumption in planning or modeling responses. As the dynamics of the situation change due to the spread of a fire or a hazmat plume, or changes in a weather system, so do the areas affected and the available options for response or evacuation. Therefore, it is very important to integrate spatially aware ABM with time-aware GIS for simulating and evaluating emergency evacuation plans and strategies.

Integration between ABM and GIS may sound trivial, but is very difficult to do effectively, particularly as the complexity of GIS data and the amount of agents increase (Kennedy et al. 2009). In current GIS environments, applying agent-based modeling to geospatial simulations is rudimentary. Modeling the temporal dimension of geographic space has achieved some success (Hornsby and Yuan 2008). However, not much progress has been made to couple both in a single framework. Furthermore, most existing studies that tried to integrate ABM with GIS did not consider the dynamics of the environment, nor did they provide an efficient solution to the integration (Kennedy et al. 2009). How to communicate time-varying information from the environment with intelligent and adaptive agents effectively remains as a challenge. The advantages of Geographic Information System (GIS) in visualization, geoprocessing, and analysis have yet to be realized for large-scale ABM studies.

This study would serve as a fundamental move to advance dynamic modeling in GIScience. This research will provide a more effective and efficient means to agent-based modeling in a geospatial context, particularly for emergency evacuations, enabling a very important class of applications in future research. The research methods will be highly adaptive to network dynamics and agent spatial mobility, which renders our architecture more robust, efficient and scalable. Applying the framework to emergency evacuations, this study can advance our understanding of the evacuation process and help evaluate the options available in an evacuation; therefore, leading to the design of effective evacuation plans. Although the primary focus is on evacuations, the framework will lay the ground for modeling other types of network-based movements in a geospatial environment. The framework and methodology can be extended from evacuation to other network-related geographic phenomena, e.g. the impacts of flash floods and snowstorms on commuter traffic.

2. RELATED WORK

2.1. Spatially Aware ABM

Agent-based modeling, sometimes called individual-oriented or distributed artificial intelligence-based modeling, is a powerful technique for simulating individual interactions and capturing group behavior resulting from individual interactions in a dynamic system. The two basic components of agent-based modeling are a model of the agents and a model of their environment (Deadman 1999). The agents are intelligent decision makers that can perceive changes in their surroundings and react to the changes (Bennett and Tang 2008). The environment could be purely a milieu that does not have impacts on agents, or it may affect the behavior of the agents. When the environment represents the geographic space in which the agents are situated, the models are called spatially explicit (Gilbert 2008). In agent-based models, a set of rules is used to govern how agents behave and interact with other agents and their environment. Compared to traditional methods, agent-based modeling holds the promise of modeling individual heterogeneity and capturing the emergence in a natural way.

A key feature of agent-based models is that the agents can detect their environment, communicate information to each other and adapt their behavior on the basis of the interactions (Gibert 2008). However, most agent-based software packages typically do not provide good support for representing complex adaptive spatial processes (Tang 2008). Few studies have attempted to couple GIS with agent-based modeling, especially when a large number of agents are involved.

It was not until the mid-1990s that ABM started to feature in the geographical literature (Castle and Crooks 2006). This is largely due to the great challenge of structuring and communicating GIS data for dynamic agents (Gilbert 2008).

The nature of the challenge lies in the representation of phenomena. The environment or social phenomena are specified as process models while GISs are specified as data models (Raper and Livingstone 1995; Brown et al. 2005). GIS data model has achieved great success in dealing with the spatial aspect of geographic data, but not in the temporal dimension. GIS data models and structures to store and visualize attributes of an object in different temporal states (Castle and Crooks 2006) are still in their infancy. Thus, GIS fails to address the dynamic nature of geographic phenomena. Agent-based models, as a type of object-oriented process model, are capable of updating the temporal behavior of objects. The difference in the model structures between ABM and GIS makes them difficult to merge. Therefore, communicating between both and representing the adaptive process in a single framework remains as a great challenge.

Most existing studies, although focused on combining GIS with agent-based modeling, failed to address how agents effectively interact with their immediate environment in a GIS platform (Kennedy 2009). That is, how to make the agents truly spatially aware. The heterogeneity of individual decision makers is also a challenge. Each individual may perceive the geographic space differently with respect to their own knowledge and experience. Thus, it would be computationally costly to query the underlying GIS, feed the agents, and return the actions.

Brown et al. (2005) suggested that a middleware approach to couple GIS and ABM is more practical and effective to take advantages of both GIS and ABM. Their effort eventually led to the formation of Agent Analyst, an agent-based modeling extension in ArcGIS. In collaboration with Environmental Systems Research Institute (ESRI), Argonne National Laboratory's Center for Complex Adaptive Agent Systems Simulation developed the Agent Analyst toolkit (Redlands Institute, 2006). It handles the actions of agents through Repast (Recursive Porous Agent Simulation Toolkit) and the topological relationships by ArcGIS. The toolkit is an example of mid-level integration of ABMS and GIS. However, in order to effectively use this tool, one has to have programming experience. Furthermore, it does not really provide an effective communication between agents and the GIS environment. Agents are designed to move in x, y space independent of the GIS and then linked back to ArcGIS by feature data updates (Johnson and Maguire 2007).

Bennett and Tang attempted to construct a spatially explicit agent-based simulation framework (Bennett and Tang 2008). Tang (2008) presented the framework with a supporting software package - the Geographically-Aware Intelligent Agent Simulation Package (GAIASP), to explore complex adaptive geographic systems. Central to the GAIASP, machine learning techniques enabled the agents to adapt their behavior to the environment. Unlike most other agent-based software packages, GAIASP provides better GIS capabilities, including geoprocessing and visualization. In another endeavor, Sahli and Moulin (2009) proposed a multi-agent-based geosimulation framework (EKEMAS) to support planning in a real large-scale environment. The agents achieved their spatial awareness through spatial perception and navigation.

2.2. Time-Aware GIS

When an environment serves purely as a medium with no effect on the agents, the environment does not impose any modeling challenges in ABM. In such a case, the geographic space only adds something visually pleasant. To account for the effect of the environment on individual agents, making agents spatially aware is essential. In such a situation, the geographic space may be static or dynamic. For example, a static geographic space is sufficient to simulate how agents transverse a landscape. However if a change in the environment would affect the agents' decisions, a dynamic representation of the geographic space is necessary. What is more important, the agents would need to detect the environmental changes and adapt to the new parameters. The big challenge here is how to simulate the environmental changes and at the same time update the information and pass it to the agents over time. In the case of an evacuation from hazardous material explosions, the footprint of the plume needs to be updated in order to move the people located closer to harm away more efficiently. The dynamics of geographic space, here, refers to time-aware GIS.

If the research on spatially aware ABM is limited, studies coupling spatially aware ABM with a time-aware GIS are even fewer. This is because dealing with time-varying data is still an emerging research area in GIScience (Gibert 2008), not to say communicating time-varying data with intelligent and adaptive individual objects. Using a loose coupling approach, a project done by RedfishGroup for the City of Santa Fe Fire and Police Department represents a recent move toward this direction (Thorp et al. 2006). By integrating wildfire simulation with agent-based modeling of traffic dynamics, the project simulated how traffic changed upon the spread of fire. However, there is still a need for a systematical framework of integrating spatially aware ABM with time-aware GIS. This study would represent a major move to reduce the gap and provide a foundation for coupling ABM and time-aware GIS.

2.3. Agent-Based Modeling of Evacuation

Based on the level of detail in modeling evacuation flow, evacuation studies can be classified into three categories: macroscopic, mesoscopic, and microscopic. Macrosimulation focuses on aggregated evacuation flows, mesosimulation takes into account driver behaviors based on small groups, and microsimulation emphasizes individual characteristics of each evacuee/vehicle (Hoogendoorn and Bovy 2001). At the microscopic level, agent-based modeling could demonstrate its great advantages in creating realistic scenarios that incorporate choices made by evacuees. When properly used, agent-based modeling can create a reasonably realistic and workable forecasting model that emergency managers and planners can use to improve the effectiveness of evacuation procedures.

Prior to 1990, due to insufficient computational power, few agent-based studies in emergency evacuation were documented. In order to reduce the computational burden, most early microsimulation models were designed only to model small-scale evacuations on primary road networks and were quite simple (Peat et al. 1973, Moeller, Urbanik, and Desrosiers 1981, Tweedie et al. 1986, and Stern and Sinuany-Stern 1989). With the advent of newer computer technology and more advanced software systems, there has been a surge of agent-based modeling in evacuation analysis since 1990. Agent-based modeling has helped evaluate the effects of various factors on evacuation performance, which is costly or not feasible in real world exercises.

Two types of evacuations that have been most simulated are: room/building-based evacuations and network-based evacuations. Here our focus is network-based evacuation. Agent-based modeling of network-based evacuations utilizes car-following and lane-changing models to account for the dynamics of traffic. Most network-based evacuation studies have focused on optimization strategies or the effectiveness of introducing traffic controls.

CORSIM, Paramics, VISSIM, INTERGRATION 2.0 are among the main agent-based microsimulation software packages used for network evacuation simulations (Hardy and Wunderlich 2007). In order to capture evacuations closer to reality, details of road network settings are desired. Therefore, it is quite demanding to prepare the network if the evacuation under study involves a large geographic area. The network data models in microsimulation software packages are usually proprietary and quite different from the network data model in GISs. Therefore, it is often a daunting task to convert a GIS-based network data layer to be used in microsimulation software efficiently. These microsimulation software packages provide some visualization capabilities. However, except for the driving units and networks, the visualization of the environment is basically static. Because traffic dynamics is the sole consideration in simulation, it is nearly impossible to evaluate the effects of environment changes dynamically other than the network system on driving behaviors. How to take the advantages of GISs in representation, geoprocessing, and analysis for agent-based evacuation studies remains as a challenge.

3. APPROACH AND METHODS

3.1. Conceptual Framework of the Spatially-Aware and Time-Aware GIS

The conceptual framework of the proposed system consists of four components: mobile agents, behavioral rules, an activity space in which the agents are situated, and a geographic space (Figure 1).

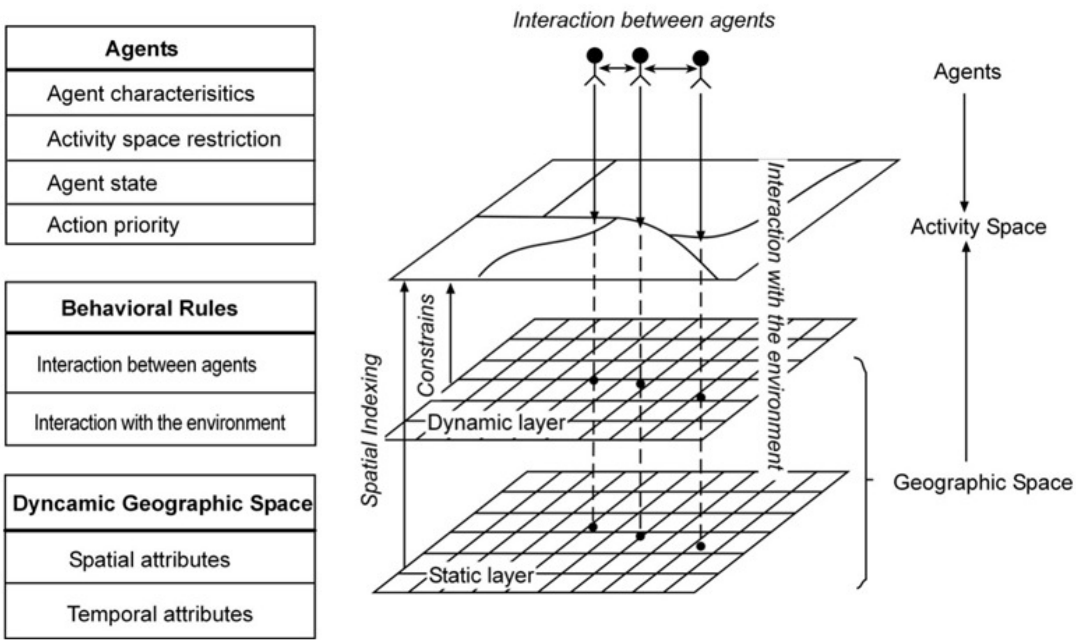

Figure 1. Framework for a spatially aware ABM based on dynamic GIS layers

(a) Mobile agents: the agents are individual intelligent decision-makers that can detect the changes in their activity space and environment. In the proposed work, vehicles are treated as individual agents. The attributes associated with the agents include vehicle types and models, capacity, and other physical characteristics. The movements of the agents are constrained by behavioral rules, the activity space, and the geographic space. Each agent is assigned to an origin. Each agent has a goal to implement – to reach its destination at the end of the evacuation.

(b) Behavioral rules: behavioral rules define how agents react in interactions with other agents and their environment. Typical behavioral rules in traffic modeling include rules for acceleration, deceleration, lane change, and response to traffic signs and lights. It is worth noting that the dynamics at the system level would impact the behavior of the agents as well. For example, congestion would cause some agents to change their routes to ones that they perceive would take less travel time based on their localized knowledge.

(c) Activity space: the agents in the proposed project are mobile objects that move along road networks. So the activity space here refers to the network-based activity layer. The movements of the agents are restricted to road network space. The properties of the activity space are defined by the transportation network under study, including attributes of links and nodes, origins and destinations of the agents. Considering road closures resulted from toxic plume spreading, the activity network layer is segmented with binary changeable states determined by the attributes of the dynamic geographic layer.

(d) Geographic space: geographic space can be categorized into different layers, as being either static or dynamic, i.e., unchangeable, or continuously changeable, respectively. The geographic space is represented through stacked dynamic and static layers. Static /spatial attributes of the geographic space represent the landscape of the environment, such as land use/cover, elevation, etc. The dynamic layer in the geographic space represents the temporal changes in the environment, such as the spread of toxic plume during the evacuation process. Based on the changes in the geographic space, the system will determine the roads that become impassible and update such information in the activity space layer. All the layers, either dynamic or static, offer an environment with all the relevant information required to accurately represent the emergency evacuation scenarios.

3.2. Build a spatially aware ABM system based on NetLogo toolkit

Agent-based models are comprised of multiple, interacting agents situated within a modeled or simulated environment. Using existing simulation/modeling toolkits can greatly speed up the development of agent-based models. These toolkits provide reliable templates for designing, implementing, and visualizing agent-based models. As a benefit, ABM modelers can focus on designing effective models and defining behavior rules to save time on building basic tools for a computer simulation (Crooks 2007).

In this study, the NetLogo toolkit was chosen to build the spatially aware ABM because it is capable of building large, complex, multi-level, agent-based models for simulating natural and social phenomena.

NetLogo was originated from StarLogo (http://ccl.northwestern.edu/netlogo/) and is under development since 1999 by Uri Wilensky and his team and is currently maintained by the Center for Connected Learning (CCL) and Computer-Based Modeling at Northwestern University. NetLogo is a freeware and can be downloaded and used without restriction. Because it is written in Java, it can run on all major computing platforms (Tisue and Wilensky 2004).

NetLogo uses a multi-agent programming language that was originated from a mix of StarLisp (Lasser & Omohundro 1986) and Logo (Papert 1980). NetLogo supports programmable mobile agents called "turtles", which can move around on a grid of "patches" concurrently. Patches are also agents and can interact with neighbors and mobile agents. In addition, there are two other types of agents in NetLogo: links and observers. Links are agents that connect turtles. Observers create views for monitoring the world made with turtles, patches, and links. Based on predefined decision rules, all of the agents can interact with each other and perform multiple tasks simultaneously.

NetLogo is also among the few ABM toolkits that directly support the input of geospatial data, especially vector-based data for traffic modeling. Since the NetLogo 4.03 release, shape files, a commonly used GIS data format from ESRI, are directly supported, making integration of GIS and ABM much easier.

The following flow chart shows how the basic behavior rules and logic will be implemented in the spatially aware ABM for evacuation modeling (Figure 2).

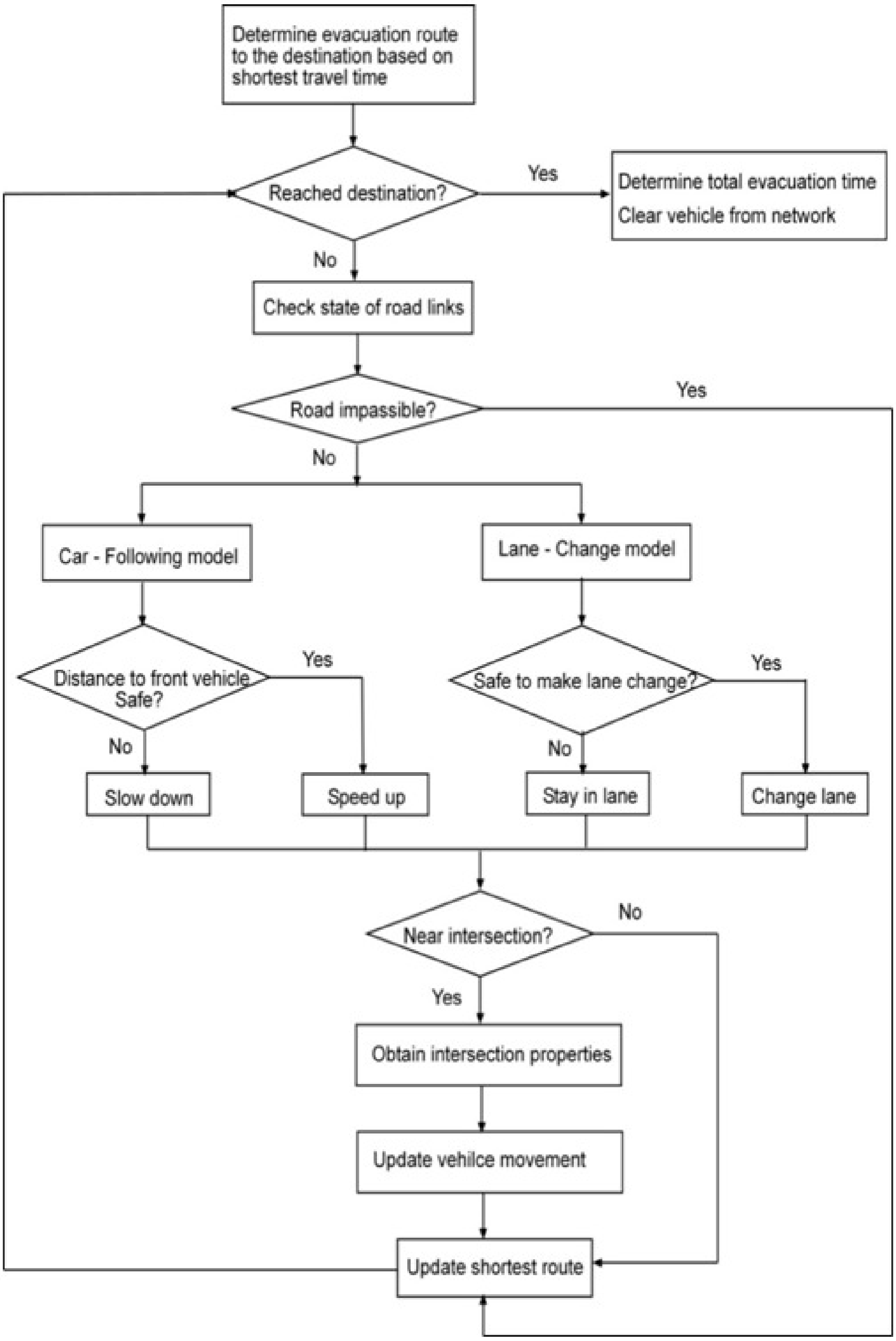

Figure 2. Flow chart for building the spatially aware ABM for traffic modeling

a. Develop the road network system for an evacuation area. The shape file of the road network for an evacuation area can be imported into Netlogo. Then attributes for roads, such as speed limit, number of lanes, and width, and intersections, such as traffic signs, and lights can be defined.

b. Set up the origins and destinations of evacuating vehicles. Depending on the type of evacuations, the origins of evacuating vehicles could be residence locations or workplaces. The destinations could be predefined places or any places that are outside of the harm, e.g. shelters or hotels. The goal of the agents is to reach the destinations within the shortest travel time.

c. Build the car-following model and lane-change model to simulate the interactions between evacuating vehicles. Based on a set of parameters, such as distance between two adjacent vehicles, speed difference between the two vehicles, posted speed of the roads, etc, the car-following model determines whether the following vehicle should accelerate or slow down. The lane change model follows similar logic. But it also checks the presence of vehicles on the adjacent lane, the distance to the vehicle, and the speed of the vehicle. At intersections, traffic rules according to traffic signs and lights moderate the movements of vehicles at intersections.

d. Optimize the evacuation routes for agents. Based on the congestion level on the road network, the system updates the shortest route for each agent based on the shortest travel time en route.

Figure 3 shows an example of how this model can be applied to a no-notice evacuation following a hazardous material release at a chemical plant owned by Pelron Corp in west suburban Lyons in the Chicago area. According to Greenpeace (CTDN 2009), a terrorist attack or accident would cause a catastrophic release of ethylene oxide gas from the plant. The entire risk zone of the plant extends beyond 10 miles. More than 1.6 million residents of Chicago's southwest side and near suburbs would be at risk if toxic gas escaped. Midway Airport, nearly 200 schools, and four hospitals are within a five-mile radius of the plant, putting the area in grave danger should an accident happen. The ALOHA dispersion model developed by National Oceanic and Atmospheric Administration (NOAA) and the Environmental Protection Agency (EPA) (NOAA 2007) can be used to estimate the threat zones associated with accidental toxic releases. The modeling system will incorporate the change of the plume footprint and update the accessibility of road segments dynamically in the area. For example, if the road segment is inside the plume footprint, the road status is set as impassible, otherwise, accessible.

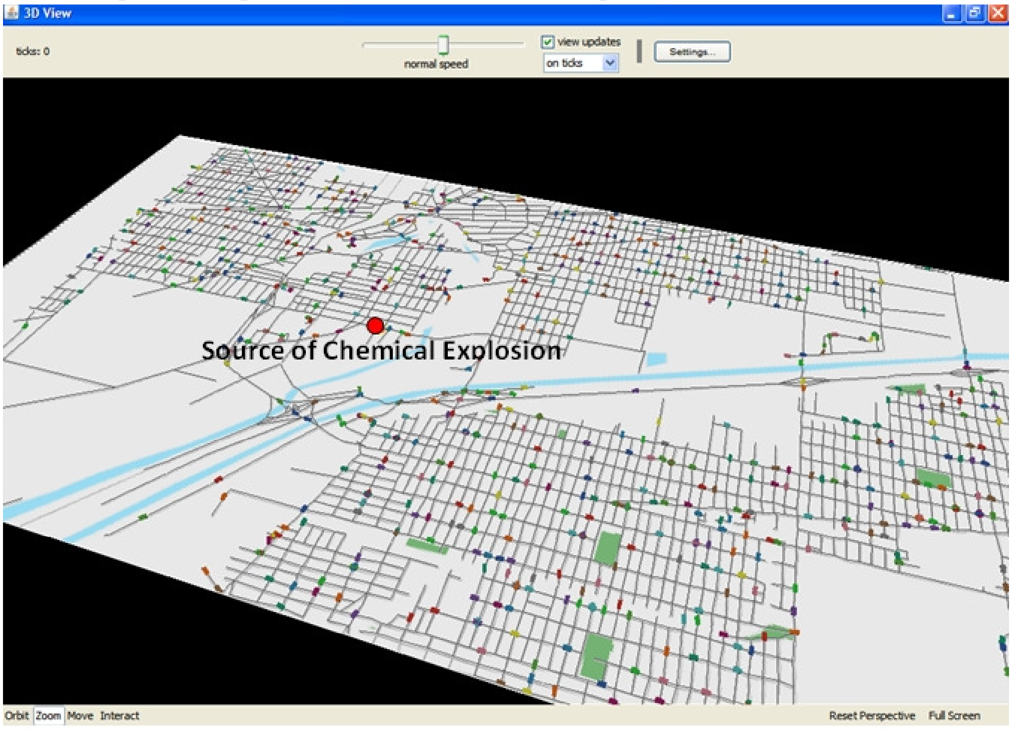

Figure 3. A prototype model built in NetLogo modeling environment with 3D view

4. FUTURE WORK

This is a long term research plan. We have built a prototype of the spatially aware ABM model with NetLogo and its GIS extension. At current step, "Car" agents are introduced with basic driving rules. They can follow the graph links and move around the network from node to node, given a realistic traffic facility. In the future, driving behavior will be calibrated using daily traffic data. Aggressiveness of drivers will be adjusted to evaluate the impacts on the evacuation process.

To build the time-aware GIS for the integration with the spatially aware ABM, this research will extend the capabilities of NetLogo GIS extension by developing a Java-based library for handling time-aware dynamic layers. The tool will allow users to step through periods of time revealing patterns and trends in the GIS environment.

Once the dynamics of the environment are captured, a coupler component will be built to communicate the status of the environment at a certain time slice to the activity space in the spatially aware ABM. This step involves a spatial overlay of the dynamic layer with the network layer. The network layer will be segmented with binary changeable states determined by the attributes of the dynamic geographic layer.

The status of the road segments will then trigger the action of agents. Whenever an agent makes a movement, it checks the state of the related road link first. If an approaching agent detects that the road is impassible, it will detour and update its shortest path to its destination.

REFERENCES

Bennett, D.A. and W. Tang. 2008. Mobile, aware, intelligent agents (MAIA). In Understanding dynamics of geographic domains. e.d. Hornsby, K.S. and M. Yuan. Boca Taton, FL: CRC Press.

Brown, D.G., R. Riolo, D.T. Robinson, M. North, and W. Rand. 2005. Spatial process and data. models: Toward integration of agent-based models and GIS. Journal of Geographic Systems 7:25–47.

Castle, C. and A. Crook. 2006. Principles and Concepts of Agent-Based Modelling for Developing Geospatial Simulations. UCL Working Papers Series, London, UK.

Chi Town Daily News (CTDN). 2009. Greenpeace targets Chicago-area chemical plant. http://www.chitowndailynews.org/Chicago_news/Greenpeace_targets_Chicagoarea_chemical_plant,31453.

Crooks, A. 2007. The Repast simulation/modelling system for geospatial system. Center for Advanced Spatial Analysis working papers series paper 123. University of College London

Deadman, P.J. 1999. Modelling individual behaviour and group performance in an intelligent agent-based simulation of the tragedy of the commons. Journal of Environmental Management 56(3): 159-172.

Gilbert, N., 2008. Agent-based models. Thousand Oaks, CA: SAGE Publications.

Hardy, M. and K. Wunderlich. 2007. Evacuation management operations (EMO) modeling assessment: Transportation modeling inventory. http://www.its.dot.gov/its_publicsafety/emo/.

Hoogendoorn, S.P., and P.H.L. Bovy. 2001. State-of-the art of vehicular traffic flow modeling. Journal of Systems Control Engineer - Proceedings of the Institution of Mechanical Engineers Part I 215(14): 283-303.

Hornsby, K.S. and M. Yuan. 2008. Understanding dynamics of geographic domains. Boca Taton, FL: CRC Press.

Johnston, K.M. and D. Maguire. Agent-Based Modeling Position Statement (ESRI). Presented at Workshop on Agent-Based Modeling of Complex Spatial Systems, April 14-16, 2007.

Kennedy, R.C., K.E. Lane, A. Fuentes, H. Hollocher, G. Madey. 2009. Spatially Aware Agents: An effective and efficient use of GIS data within an Agent-based Model. Agent-Directed Simulation Symposium (ADS'09), The Society for Modeling and Simulation International (SCS), San Diego, March 2009.

Lasser, C. and Omohundro, S. 1986. The Essential Star-lisp Manual. Thinking Machines Corporation.

Moeller M., T. Urbanik, and A. Desrosiers. 1981. CLEAR (Calculated Logical Evacuation and Response): A Generic Transportation Network Evacuation Model for the Calculation of Evacuation Time Estimates. Washington, D.C.: Prepared for the Nuclear Regulatory Commission by Pacific Northwest Laboratory

National Oceanic and Atmospheric Administration. 2007. ALOHA user's manual. http://www.epa.gov/emergencies/docs/cameo/ALOHAManual.pdf .

Papert, S. 1980. Mindstorms: Children, Computers, and Powerful Ideas. Basic Books. New York, NY.

Peat, Marwick, Mitchell and Company. 1973. Network flow simulation for urban traffic control, System-phase II. v. 1. Prepared for the Federal Highway Administration, Washington, D.C., 20590.

Raper, J. and D. Livingstone. 1995. Development of a geomorphological spatial model using object oriented design. International Journal of Geographical Information Systems 9(4):

Redlands Institute. 2006. Agent-base modeling extension for ArcGIS. http://www.institute.redlands.edu/agentanalyst/.

Sahli, N. and B. Moulin. 2009. EKEMAS, an agent-based geo-simulation framework to support continual planning in the real-word. Applied Intelligence 31 (2): 188-209.

Stern, E., Z. Sinuany-Stern, and Z.S. Holm. 1996. Congestion-related information and road network performance. Journal of Transport Geography 4(3): 169-78.

Tang, W. 2008. Simulating complex adaptive geographic systems: A geographically aware intelligent agent approach. Cartography and Geographic Information Science 35(4): 239-263.

Thorp, J., S. Guerin, F. Wimberly, M. Rossbach, O. Densmore, M. Agar, And D. Roberts. 2006. Santa Fe on Fire: Agent-Based Modeling Of Wildfire Evacuation Dynamics. http://www.redfish.com/wildfire/RedfishGroup_Thorp_ABMofWildfireEvacuations_v002.pdf.

Tisue, S., and Wilensky, U. 2004. NetLogo: A simple environment for modeling complexity. Paper presented at the International Conference on Complex Systems (ICCS 2004), Boston, MA, May 16-21.

Tweedie, S.W., J.R. Rowland, S. Walsh, R.R. Rhoten, and P.L. Hagle. 1986. A methodology for estimating emergency evacuation times. The Social Science Journal 21(2): 189-204.