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SANTA FE ON FIRE: AGENT-BASED MODELING OF WILDFIRE EVACUATION DYNAMICS

JOSHUA THORP*, RedfishGroup, Santa Fe, NM
STEPHEN GUERIN, RedfishGroup, Santa Fe, NM
FRANK WIMBERLY, RedfishGroup, Santa Fe, NM
MICHELLE ROSSBACH, City of Santa Fe Fire Department
OWEN DENSMORE, RedfishGroup, Santa Fe, NM
MICHAEL AGAR, Ethknoworks, Santa Fe, NM
DOUGLAS ROBERTS, RTI International, Nambe, NM

ABSTRACT:

This paper reviews a recent RedfishGroup project for the City of Santa Fe Fire and Police Department integrating wildfire simulation and agent-based modeling of traffic dynamics. Visualizations of the evacuation dynamics were used to communicate with citizens dangers faced during evacuations and to explore when shelter-in-place is a reasonable alternative to evacuation. Additional uses of the model were for use in "table top" exercises conducted by multi-agency emergency response teams and for identification of intersections and road segments expected to have high congestion. The paper reviews the modeling approach and the ecology of software tools used on the project. ESRI ArcView was used for preparing GIS data sources of housing, street centerline data, elevation maps and geo-referenced aerial infrared imaging for wildfire fuels modeling. NetLogo was used for early prototyping of both cellular automata-based wildfire models and for network-based traffic models. FARSITE was later integrated for wildfire simulation. Open-source Blender3D was a central tool for this project used for both agent-based modeling and 3D visualization. The traffic agent-based model of 50,000 cars on the Santa Fe road network was written directly in Blender using Python. The traffic visualization was combined with wildfire simulation output from FARSITE and rendered in 3D in Blender. Simulation results were deployed for community use in Google Earth and Quicktime visualizations generated by Blender.

Keywords: Agent-based modeling, wildfire evacuation, emergency planning, Santa Fe, traffic simulation, wildfire modeling, NetLogo, Python, Blender

BACKGROUND, GOALS AND APPROACH

The City of Santa Fe, New Mexico faces a wildland fire threat as do many other communities in the United States. In the City there are significant numbers of homes nestled in wild vegetation along narrow roads. Often there is only one ingress/egress to those neighborhoods. Fire Department officials began wondering in 2003 about whether residents would be able to evacuate their homes safely in the event of a fast-moving wildfire, and they began teaching citizens to be ready to evacuate or shelter-in-place depending on the circumstances.

Corresponding author address: Joshua B. Thorp, RedfishGroup, 624 Agua Fria Street, Santa Fe, NM 87501; email: josh@redfish.com

In Santa Fe, City officials initiated a collaboration with agent-based modelers and visualization scientists at RedfishGroup and with fire scientists at Anchor Point Group of Boulder, CO to develop models of the interaction between massive but not unrealistic wildfires and traffic as it would exist in an evacuation (the 48,000 acre Cerro Grande Fire, which destroyed over 200 homes in Los Alamos, was visible from Santa Fe). The goals are not only disaster response planning (Figure 1) but also education of citizens and first responders. City emergency response professionals hope that the ability to visualize a fast-moving fire and its accompanying smoke and their dramatic effect on traffic will serve as an effective educational tool and as a means to illuminate the controversy.



Figure 1: Agent-based models and visualizations were designed to augment existing “table top” exercises used by multi-agency emergency planners.

The local effort has not been without controversy, however; many wildland firefighters (and police officers) in the area insist that all citizens will be able to evacuate in all circumstances. The controversy over “sheltering-in-place” during wildfires exists nationwide and is described more in-depth elsewhere (“Emerging Issues”, 2004). As a quick point, shelter-in-place is not a recommended option in many communities because of the type of wildfires expected and the prevalence of certain materials in construction (eg shake-shingle roofs). Some experts within the Santa Fe Fire Department and elsewhere, however, believe that due to local conditions, shelter-in-place is a viable alternative worth communicating to the citizens in Santa Fe. Local adobe and stucco construction with flat tar and gravel roofs are estimated to withstand direct flame for about 25 minutes while the type of wildfire expected (crown fire moving through pinon-juniper fuels) is expected to pass within 7 minutes. It is argued that if the evacuation routes are congested, a family may be safer in their house than stuck on the road in their car.

THE APPROACH

The three components of the work are: Fire Modeling, Traffic Modeling, and Visualization. The architecture that combines these will be described below.

Fire Modeling

In early explorations we developed a cellular automata (CA) approach to modeling the spread of fire over a terrain. In this approach we divided the area into a grid of small squares. When a fire ignites in a cell, the probability of a neighboring cell igniting depends on the wind, the elevation difference and the fuel available. Simply speaking, a cell is more likely to ignite if it is downwind and uphill from an already burning cell.

As the project advanced, however, more realism and credibility of the fire model were needed and we acquired Farsite for the fire modeling component of our work. Farsite is widely used in the Forest Service and others with an interest in wildfire science. It is part of a suite of programs, including FlamMap and Behave, that are based on first principles of fire physics. One of the pivotal papers in the area was published by Rothermel in the early 1970's (Rothermel 1972) and all of these programs are based on the physics described there. He created a model that combined conservation of energy and empirical measurements of fire spread in wind tunnel experiments.

Sullivan and Knight (2004) point out that CA models of "bushfires" (wildfires in Australia) have been less successful than hoped. According to them, models based on nearest neighbor ignition rules are too naïve. They say that empirical fire spread models such as Rothermel's are not true CA models since they are calculated on a raster or lattice. They propose a hybrid approach which they call cellular automata/semi-physical models.

The main input to a Farsite run is a landscape file. This is a file which combines elevation, slope, aspect, fuel and canopy data. In addition, a Farsite run take in to account weather data including wind, temperature and humidity. For most wildfire simulations in this project, we used extreme conditions: 98 degrees F, 40 MPH winds and 10% relative humidity. These values are the norm in April-May when wildfire risk is at its highest in Santa Fe.

Initial landscape files were constructed from digital elevation maps (Figure 2), landcover and canopy data (Figure 3) that we obtained from the USGS web site. We used ArcGIS 9 to assemble the aspect and slope data from the elevation data. In parallel with our project, the city of Santa Fe contracted with Anchor Point Group to develop a landscape file for its wildland/urban wildfire studies. Their work included analyzing the fuels in the area and characterizing the ignitability of the local structures. The area of interest was flown with aerial photography (6"/pixel resolution) in the spring of 2006 which included infrared imaging to better

resolve fuel and canopy cover. We produced animations early in the project showing this imagery *texture-mapped* onto 3D topography (Figure 4).

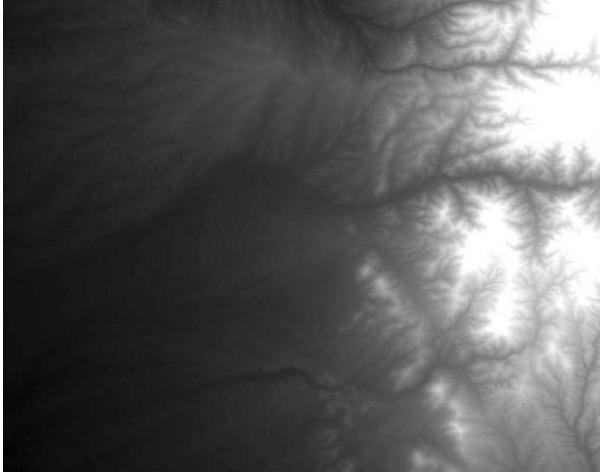


Figure 2: Digital Elevation Model of Santa Fe

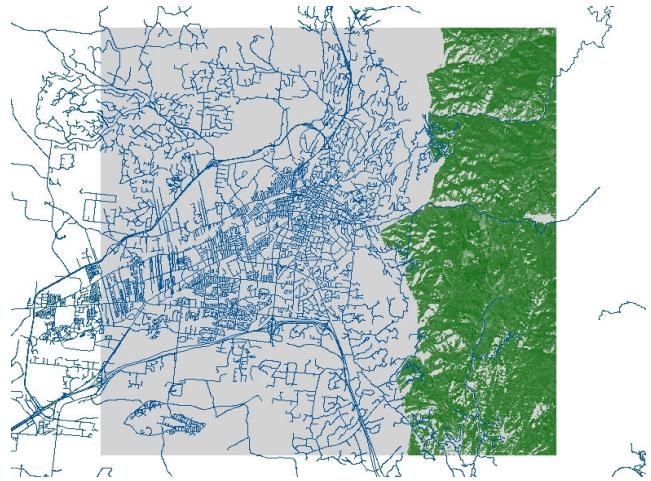


Figure 3: Canopy Map for Santa Fe

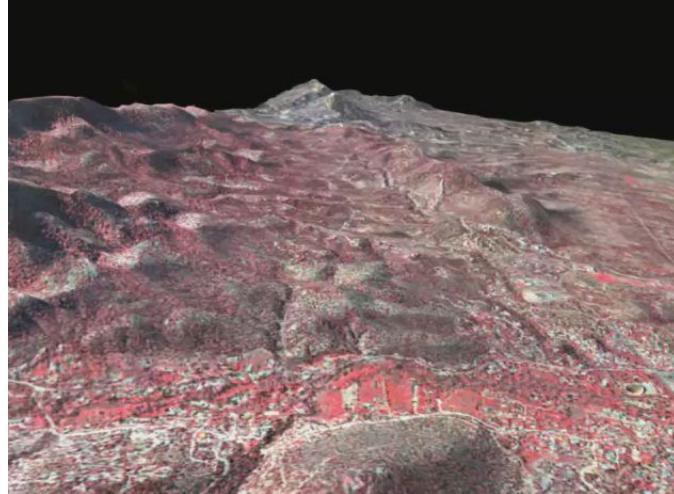


Figure 4: Infrared aerial photography *texture-mapped* to Santa Fe topography

Farsite has a variety of output options including the ability to create raster files describing the simulated fire. The types of raster files include, for example, time of arrival (when does the fire reach each point in the area), flame length, fireline intensity, spread direction and crown fire activity. These can be displayed in ArcGIS or, more importantly for our purposes, they are in a standard format which is easy for our visualization software to render.

After receiving the landscape file from Anchor Point, we “ignited” a number of simulated fires around Santa Fe in order to get simulations of the fire/traffic interactions in a number of kinds of city neighborhoods. We focused, however, on areas which we knew would be challenging to evacuate in the event of an aggressive crown fire. The body of research produced by Cova et al. (Cova 1997, 2002, 2003, 2005a, 2005b) provides good background and many valuable techniques for characterizing relative neighborhood evacuation risk.

TECHNICAL DESCRIPTION OF THE WILDFIRE EVACUATION MODEL

The Wildfire Evacuation Model explores the interaction of two complex systems; a traffic model and a wildfire model. Combining two models with different time steps and architectures is a challenge in agent-based modeling, especially when the models are directly affecting each other. Cars blocking roads in an emergency evacuation could hinder fire crews preventing them from reaching the fire. This would cause the fire crew’s attack on the fire to be hampered by the dynamics of the traffic model with a resulting change in fire model behavior as compared to an ideal fire attack (i.e. one with immediate fire crew presence). As the fires most likely to affect Santa Fe would be fast moving (up to 5 km/hour), we assume that only fires where the initial attack was unable to control the fire would rise to the level of evacuation. Thus this model can be considered the worst-case situation of no fire attack allowing the assumption that fire dynamics are independent of the traffic dynamics. This leaves the fire model free to be run independently of the traffic model and to serve as input to the traffic model. Below we detail the traffic model GIS inputs and traffic behavior including the wildfire model impact on the traffic model.

Traffic Model

Initial explorations in modeling intersections was prototyped in NetLogo (Wilensky, 1999) with the road network modeled as a graph with nodes and edges (Figure 5). As an aside, our team continues to find NetLogo invaluable as a powerful rapid prototyping environment for agent-based models while it remains approachable to domain experts that don’t normally identify themselves as coders.

As the number of cars in the traffic model increased up to 70,000 and the GIS components grew in importance, development was transitioned to Python (<http://www.python.org>) and visualizations in Blender3D (<http://www.blender.org>), an open-source 3D modeling and animation environment (Figure 6). Blender has integrated python scripting and was used as both view and control of the model. Input to the traffic model consists of many GIS data files. GIS data comes in raster and shape (vector) file formats. In our model we use both type. These files were imported into the Python implementation of the traffic model using the Geospatial Data Abstraction Library (GDAL) (<http://www.remotesensing.org/gdal/>) for raster type and the Python bindings to the Shapefile C Library (shapelib)

(<http://shapelib.maptools.org/>) for shapefile type data. These format types are just like formats one will have dealt with in paint programs such as Adobe's Photoshop (raster) and Illustrator (vector). In simple terms raster files consist of a grid of pixels with a certain width and height, with each pixel having some value (such as elevation). A shapefile has a vector-based format that consists of descriptions of shapes such as lines, curves made up of lines, called poly-lines, and polygons.

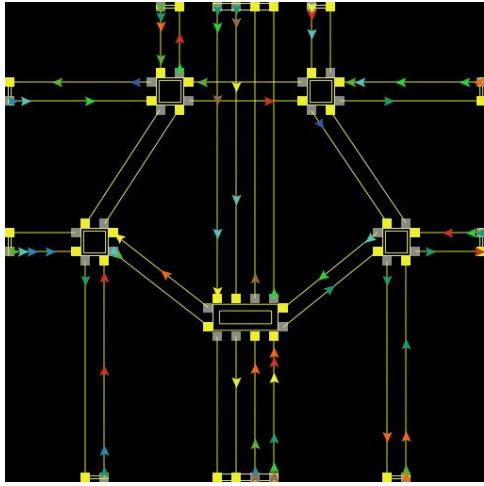


Figure 5: Traffic prototypes in NetLogo

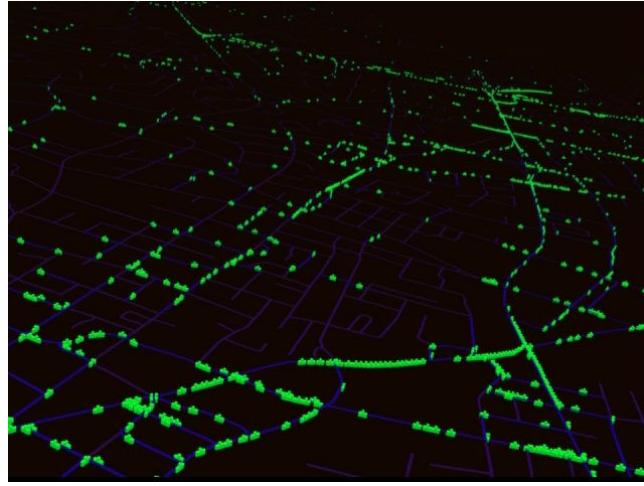


Figure 6: Full-scale traffic models implemented in Python/Blender

Agent-based models typically consist of agents interacting with each other in an environment. In general an environment may consist of cells in a grid with a topology of four or eight neighbors or a network (graph) topology. The traffic model's environment is constrained to the topology of the streets of Santa Fe as input in a shapefile. The shapefile consists of shapes called poly-lines -- shapes that are made up of a number of line segments -- and is a description of the 'center line' of the streets of Santa Fe. From this information a road network is built. Roads consist of multiple lanes proceeding from a directional distance of zero at one end to the total length of the road at the other. Each road has at least one lane that has directionality and a distance of zero at one end of the road proceeding to the length of the road at the other. Depending on the number of lanes and whether the road is 'one-way', roads may have lanes beginning at both ends of the road. The cars exist on lanes that meet at intersections and can pass from one lane to another at intersections based on the connectivity of the intersection (Figure 7). Lanes that enter an intersection are connected to lanes that exit that intersection.

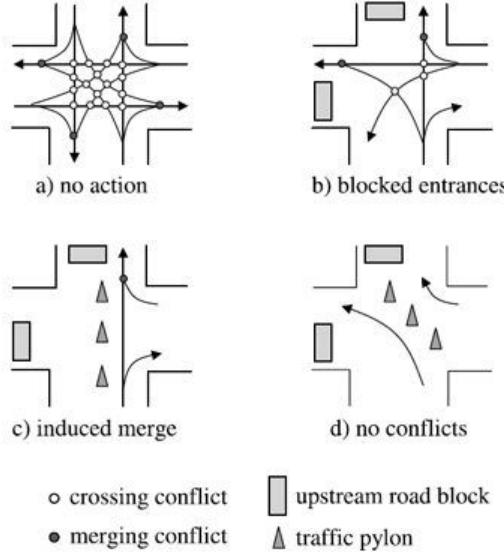


Figure 7: Modeling of intersections with merge and crossing conflicts based on Cova (2003)

Car agents are aware of their neighbors sharing a lane, a road, or an intersection. Cars are not aware of their absolute positions in space such as elevation or north or east location as they exist at a distance along a lane in this world of roads and intersections. Cars are aware of their neighbors in this space, avoid collisions, accelerate and decelerate, and turn at intersections following a mixture of local rules and seeking a destination.

Predetermined sets of origins and destinations are defined in the model. At the beginning of a model run cars are assigned a destination and an origin location based on the real locations of homes in Santa Fe. This is informed by the locations of actual Santa Fe homes from another GIS data file. Destination points may include an evacuation center or road that leads out of town and conceivably be extended to various other destinations, such as area hotels.

All intersections in the model are informed of the distance to destination points through an initial ‘flood-fill’ from these points. This technique is useful when there are only a handful of possible destinations; however, it is memory and CPU-intensive for a large number of points. This evacuation model is not so much concerned with the destination as with the dynamics of leaving the evacuated areas. Careful selection of evacuation points allows us to produce realistic sets of local routes out of the evacuated area. From that point cars, follow a set of local rules choosing particular routes at intersections according to the capacity of roads, their distance to the goal as determined by the flood fill, with aversion to changing roads too often, and certain amount of random noise that we refer to as the ‘tourist factor’ that serves to give drivers an incomplete knowledge of the roads. Added to the above is general aversion to driving on or near roads that are near active fires. Possible further work in the social modeling of the evacuees would be necessary to determine where in particular populations would drive to, including friends and family homes, hotels, and other locations outside of the evacuated area.

Impact of Wildfire Model on Traffic Behavior

The fire model output from the Farsite wildfire model consists of eight raster files of which the “Time of Arrival” (TOA) and “Flame Length” (FML) files are currently used as input to the traffic model. The TOA file consists of a geographic area covered by a grid of pixels. Pixel values are either the fractional hour that fire first enters that pixel or “-1” if no fire ever entered the area. Shape files generated from simulations in Farsite were imported into Google Earth Pro (<http://earth.google.com/>) so that they could be shared with citizens of Santa Fe as .kmz layers. The Pro version of Google Earth is only required to generate the .kmz files from .shp files. The .kmz files are then distributable to end-users with the free version of Google Earth. See <http://www.redfish.com/wildfire> for more examples.

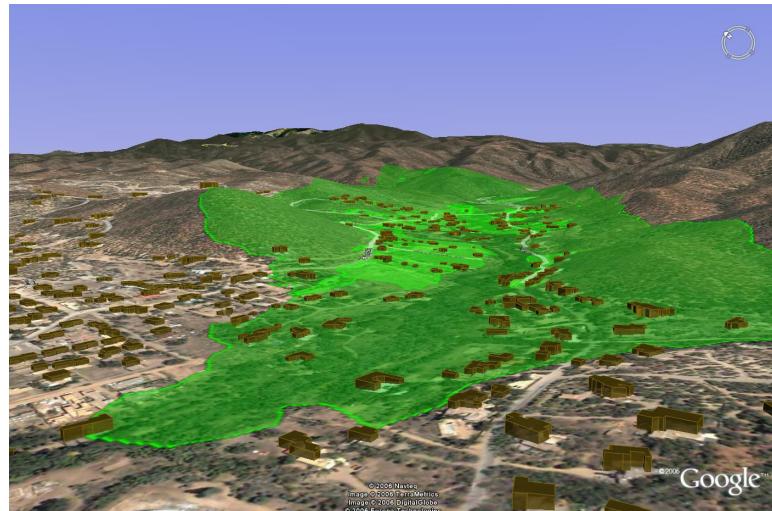


Figure 8: Extent of wildfire in the first hour. GIS shapefiles imported into GoogleEarth

The traffic model takes this information as input and sorts fire points according to start of fire. As the traffic model reaches the time when a fire first appears that point is added to a set of current fires and roads that are near these fires are impacted as are roads that are located downwind of the fire. These points last for a certain time based on the estimate of duration of fire given the fuels at that location, before they are removed from the list. This information is made available to nearby roads, which can then be queried by cars traveling on these roads for deciding whether to turn at an intersection. Finding fire or smoke on a road, the car will avoid that road.

Blender 3D

Visualization of the model is produced in the Blender environment. Blender is a sophisticated 3d modeling, animation, and rendering environment with Python scripting built in.

This allowed us to control the run of the model from within the Blender tool and render cars, fire, and Santa Fe elevation data from the area of interest Digital Elevation Model (DEM) in 3D animations (Figure 9).



Figure 9: Rendering of smoke, Farsite *Time of Arrival* and *Flamelength* with Blender3D

Animations, reports, images and source code (released under LGPL) for this project can be found at <http://www.redfish.com/wildfire>

RESULTS AND FUTURE WORK

At the beginning of this project, we anticipated that the primary value delivered would be the evaluation and optimization of traffic evacuation routes and plans. However, we discovered early on that existing evacuation plans in the city were relatively unsophisticated – eg, “go downhill and meet up at the local rodeo grounds, the planned emergency shelter”. The cause for this was not due to an unsophisticated city management – In fact, we found the employees within the city to be among the most professional of any organization we encountered. The unsophisticated plans, we suspect, is more due to that fact wildfires can occur practically anywhere in a city. This is in contrast to something like hurricane evacuation planning, where planners know the threat will start from the coast and move inland and can publish planned evacuation routes. We now think the best you can do in wildfire planning is run different scenarios and look for common patterns in traffic congestion. For instance, which intersections consistently become bottlenecks and warrant police presence to direct traffic. Additional areas of research can be into more demand-based scheduling algorithms for traffic signals along the lines of Gershenson, 2005.

Additionally, a real value delivered can be to raise the awareness of the citizens to the possible contingencies. As the project progressed efforts focused more than planned on modeling the wildfire dynamics than the traffic dynamics so that we could get a better sense of the typical risk Santa Fe was facing. Visualizations of potential wildfire scenarios have been very effective at raising public awareness and they serve as backdrop to discussions involving hard decisions facing the community like fuel thinning projects.

Visualizations of the wildfire dynamics coupled with trapped cars on narrow roads helped frame the question of evacuation vs. shelter-in-place for citizens. Prior to viewing the visualizations, many citizens assumed they could outrun a fire. They did not realize fire-spotting could advance in front of them or how much of an issue smoke would be during evacuation. The project has helped people realize that they may be shelter-in-place may be a last-resort option that they may be forced to take. Preparing their house to survive a wildfire then becomes less about saving a structure and more an issue of potentially saving their family's lives.

Work is ongoing to further make the simulations accessible to emergency planners. We're currently working with Sandia Labs to develop *augmented-reality* tabletops that will allow us to project simulations down on to tables while allowing planners to manipulate real-world objects like fire trucks, fire attack aircraft, wind vectors, etc. on the simulation table. Cameras and RFID tags embedded in the objects allow for real-time feedback on object positions to the simulation. We expect this will provide a more collaborative environment unmediated by personal computer terminals.

ACKNOWLEDGMENTS

RedfishGroup would like to thank employees of the City of Santa Fe that provided much time helping us understand the issues on this project. We would also like to thank the Santa Fe Institute for hosting a workshop where the team was able to meet with city planners and review the models. And lastly, we'd like to thank members of the FRIAMGroup in Santa Fe for their feedback and suggestions on this project.

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