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GIS SIMULATION AND VISUALIZATION OF COMMUNITY EVACUATION VULNERABILITY IN A CONNECTED GEOGRAPHIC NETWORK MODEL

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ABSTRACT: *Accumulation of vehicles on streets and highways during emergency evacuations causes traffic jams. This study models the spatial patterns of vehicle population during an emergency evacuation in order to find the accumulation "hot spots" or vulnerable places on a street network model. The City of Buffalo was used as a study area. A geometric network model was built with edges and junctions. The distributed population of US Census block groups was converted to vehicle population, and the vehicle population was transferred to the geometric model as a weight. The ArcGIS Network Analyst extension was used to simulate the traffic flow in the distributed model. The results indicate that the highest evacuation congestion occurs on Main Street east bound. The second highest happens on Route 33 east bound, and the lowest traffic intensity occurs on Route 5 south bound. The spatial pattern of congestion does not change in the simulation with the addition of day time working population in the downtown Buffalo.*

INTRODUCTION

In emergency evacuation situations, traffic may be congested on certain road ways due to the accumulation of cars or vehicles. An emergency is a sudden, urgent, unexpected occurrence requiring an immediate action. An evacuation is the removal of persons or goods from an endangered area. Vulnerability is the extent to which a geographic area is likely to be damaged or disrupted by the impact of a hazard. A hazard is a natural or human-caused phenomenon that may occur and threaten human life and well-being (Dorge and Jones, 1999). Cova and Church (1997) pioneered the Geographic Information Systems (GIS) based community emergency evacuation study. Their study identified the communities which may face transportation difficulties during an evacuation. The research modeled the population per lane of road occupation during an emergency evacuation using the City of Santa Barbara, California as an example. However, the study is lacking in theoretical guidance to real world GIS analysis and simulation for emergency evacuations in two ways. First, the City of Santa Barbara, California is not a typical example of metropolitan urban regions in the United States of high population cluster that may encounter great difficulties during an evacuation. Second, a sophisticated philosophical model proposed in this research may well distort the attention of GIS professionals from solving the problems and simulating different scenarios. The current research provides unique original and applicable GIS analytical platform that the GIS professionals can develop a standard geoprocessing procedure for GIS based urban emergency evacuation planning.

A significant amount of research was published for the GIS visualization of population distributions (Kamp and Sampson, 2004; Crampton, 2004; etc.). Studies have also been conducted on the importance of emergency evacuation for a hurricane event, in particular regarding its cost and time-line (Pidd et al., 1996; Urbina and Wolshon 2003; Whitehead, 2003). GIS based environmental equity and risk assessment study (McMaster et al., 1997) also indicated that spatial analysis at neighborhood scale is very important in modeling the inequity and complexity of environmental risks. Goodchild characterized transportation related GIS studies as comprising three views, the map view, the navigational view, and the behavioral view. The map view shows the linear transportation network of roads, rivers, canals, and railways. The networks are a collection of links and nodes, with setbacks and intersections are subject to uncertainty. The navigational view uses optimal paths and routes; this is based on the link and node network of the map view. The behavioral view was described as attempts to follow drivers around, and deals explicitly with the behavior of discrete objects of vehicles, people, trains, boats, or sediments on and off the linear network (Goodchild, 2000). The objective of this study is to model the spatial patterns of vehicle population during an emergency evacuation in order to find the accumulation "hot spots" or vulnerable places on the street and roadway network. This study focused on two of the three views Goodchild (2000)

proposed, the map view and the navigational view. This study selected the scenario that all drivers would choose the nearest route regardless of the level of congestion. The behavioral view of individual selection of evacuation route is not simulated in this study. In general, the results of this study present the worst scenario of an emergency evacuation that often turns out to be the reality. The City of Buffalo was used as the study area. The City of Buffalo is located in Erie County, New York. It is the second largest city in the New York State with an estimated current population of 258,493 in the city itself excluding the outskirt suburban towns in the metro-areas (US Census, 2004). The land area of the city is 105.19 square kilometers. A total of 8,003 road segments are within the City of Buffalo limit; these represent 1,532 named streets in the city.

METHODS

Population distribution and demographic data was obtained from the US Census Bureau (www.census.gov). Block groups, the smallest geographic units of the US Census population survey, were used to analyze population distribution. The Census population data of year 2000 was used in this study because it was collected by actual enumeration. The road and street network feature class was obtained from the Erie County GIS office and it was updated to the year of 2000. New York State GIS Clearing House ALIS street centerline data was not used in this study simply because the dataset was published after this study was accomplished. Since the objective and focus of this study is to simulate the weight of vehicle accumulations on the street network system, the accuracy improvement of physical locations of street addresses from the local government maintained centerline spatial database by New York State does not affect the analytical process and results of this research.

The street centerline network was named the "Buffalo Roads" feature class, and it was intensively edited to include the additional behaviors or attributes of features such as the total number of lanes in each direction, speed limit, two way or one way street, etc. Field investigations were conducted in determining the speed limit and direction of traffic allowance of the street lines. The feature class of state owned roadways was obtained from the New York State Department of Transportation (DOT). It was re-projected and merged with the "Buffalo Roads" network.

A total of 412 Census block groups were identified in the City of Buffalo. A simple model was established in this research to determine the vehicle population from the residential population of block groups during an evacuation situation. The model is: Vh_Pop = Pop/5 provides five people per car. Where Vh_Pop is the vehicle population, Pop is the residential population. Three assumptions were made at the early stages of this study. First, it was assumed that the population number who drives out of the city for work is similar to that driving into the city for work. This in general regards the residential population in the city as the evacuation population in order to start the analysis. Estimated day time working population would be added to the simulations after the first phase of analysis is accomplished. Second, during evacuation the city officials would be able to make an announcement to require five passengers per vehicle in order to ease traffic jams. Third, every family will drive their own vehicle, and no public evacuation transportation will be provided. Two advantages exist of using this simple model in comparison to apply more sophisticated mathematical or statistical models. First, the simple model provides a straightforward means of computing the realistic vehicle population in an evacuation situation. Second, the model can be easily applied to various urban high population concentration areas to simulate vehicle accumulation without changing parameters.

The vehicle population was computed for each of the Census block groups. The block group feature layer with vehicle population attribute was then overlaid on the "Buffalo Roads" network to transfer and simulate the vehicle accumulations. Three new fields were added to the street and highway segments in the "Buffalo Roads" network layer, these are vehicle population one, vehicle population two, and total vehicle population. The vehicle population of each of the block groups was transferred from block group map layer to the street egress routes of the block group in the "Buffalo Roads" network feature class. The second column of vehicle population attribute was prepared for the street segments that may collect vehicles from more than one block group, although this situation seldom occurred in our study. Three levels of evacuation routes were identified: collection routes, connection routes, and major evacuation routes. Collection routes are those streets collecting vehicles directly from the communities that are represented by US Census block groups. The connection routes are those connect the collection routes to the major evacuation routes. Major evacuation routes are those transportation roadways that were selected by the City of Buffalo as the evacuation routes.

The Network Analyst extension tools in ArcGIS were used in simulation of the vehicle

accumulations. Since the network tools only work for the geodatabase format, the street and highway network, "Buffalo Roads" was converted into geodatabase feature classes. In essence, the conversion from shapefile to geodatabase created a distributed spatial network model with loadings of vehicle population. It was shifted from mapping centric to model simulation centric.

Five major evacuation routes were identified according the City of Buffalo planning board (City of Buffalo, 2005), these are Interstate 190 north bound; Interstate 190 south bound; Route 33 – Kensington Expressway and Parkway east bound; Route 5 – Main Street northeast bound; and Route 5 – Buffalo Skyway, Father Baker Memorial Bridge and Fuhrmann Boulevard/Expressway south bound (Figure 1). A new personal geodatabase was created and named "Emergency Evacuation". The feature layers of collection routes, connection routes, and major evacuation routes were imported into the "Emergency Evacuation" geodatabase as individual feature classes.

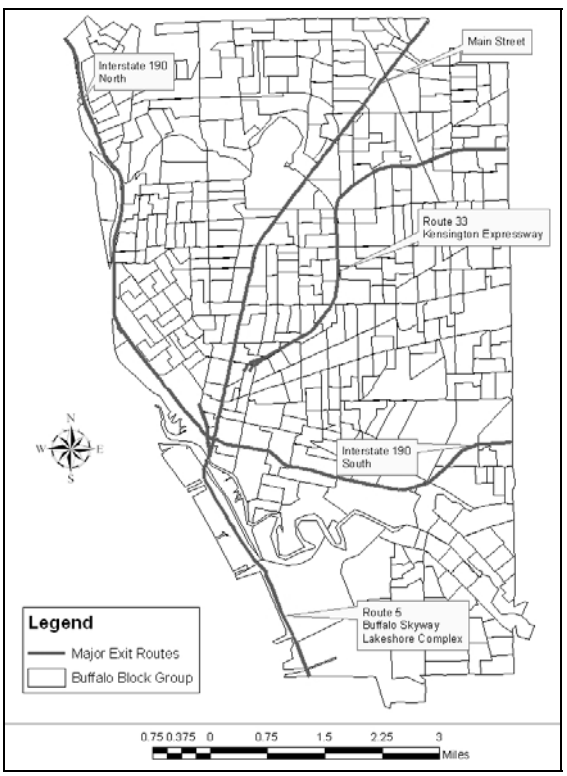

Figure 1. City of Buffalo Major Emergency Evacuation Routes (Source: City of Buffalo Planning Board, 2005).

A geometric network model of the "Emergency Evacuation" was created and named as "Vulnerability". Edges and junction nodes of traffic flow in the distributed network model were created. Three weights of traffic edges and junction nodes were created in the spatial database in simulation of traffic flow. These are lane number (number of lanes), vehicle population, and traffic jam index. Traffic jam index is a decimal number varies from 0 to 1 that was derived from the speed limit. In brief, the higher the speed limit, the lower the traffic jam index. The values of weights were inputted according field investigation database.

In the distributed geometric network model, traffic edges and traffic junctions can be identified as sources or sinks. Sources and sinks drive traffic flow through the geometric network. Sources are edge or junction features that push traffic flow away from themselves through the edges of the network. In this study, the beginning network edges that collect the vehicle population from the block groups are the sources. Sinks are edge or junction features that pull the traffic flow from other edges in the network. The ending edge segments of the five major egress routes on the boundary of the city limit were assigned as sinks. Traffic flow moves away from sources and moves towards sinks. The geometric network uses sources and sinks to determine the direction of flow along its edges. Every traffic edge or junction of the network model can be designated as either source or sink, or neutral through changing the Boolean value of the "Ancillary Role" field in the geometric network database of the Network Analyst (Figure 2).

Five evacuation sub-districts were identified in the city in relating to the five major egress routes that were identified by the City of Buffalo. Network Analyst tools in ArcGIS do not allow loops in the geometric network model in supporting the simulation of traffic flow accumulations. As soon as the validity of the distributed model was checked by the network tools, the simulation utility was enabled. The sinks or exit points were flagged as junctions with the weight accumulation flag tool. The set flow direction of the network model could be turned on that displays arrows pointing the flow direction of traffic from the residential block groups along the connecting routes to the corresponding major exit route towards the sinks. The Network Analyst tools can also be changed with weight to reflect vehicle population (Figure 3). The upstream accumulation tool can aid in visualizing where the vehicles come from and check the traffic jams on each of the traffic edges or junctions. The dots on the geometric network traffic flow modeling map (Figure 3) represent junctions where the accumulations of the weight, or vehicle population in this case, can be identified by pointing the mouse on them.

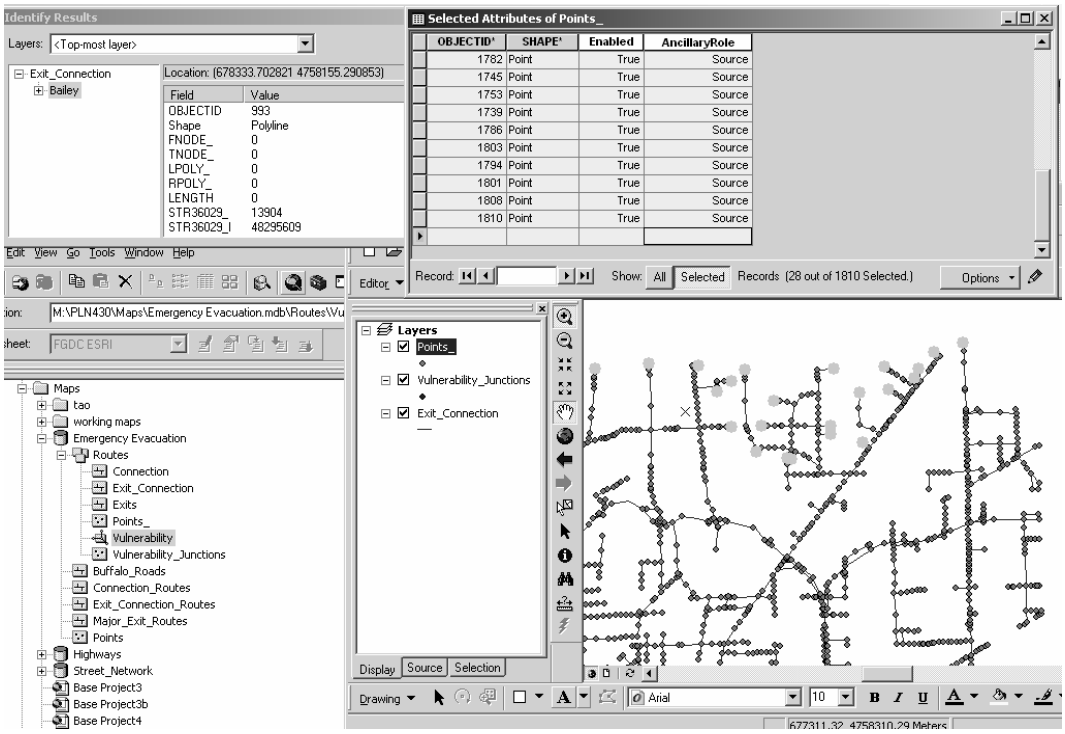

Figure 2. Designation of Sources on a Geometric Network

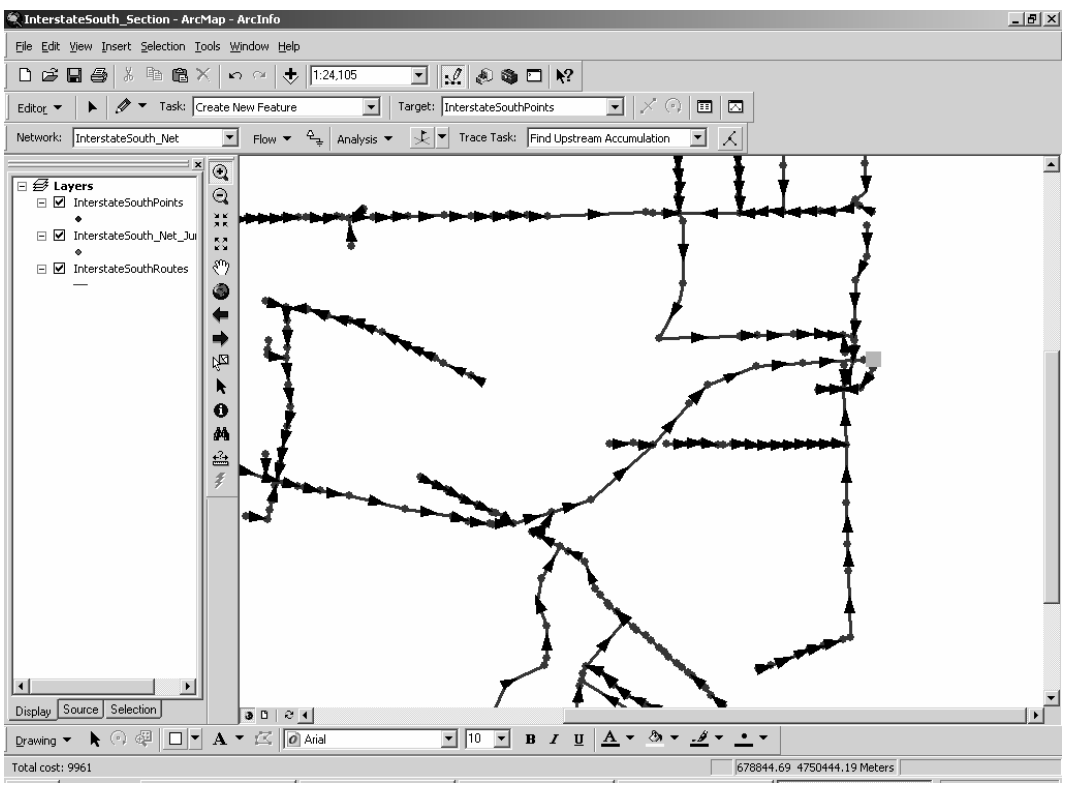

Figure 3. Upstream Accumulation Mode of the Distributed Network Model in Identifying the Vehicle Weights at Junctions (dots).

RESULTS

The objective of this research is to analyze and visualize the evacuation traffic jams on the evacuation routes in the city. The results indicate that there could be some vulnerable locations in the City of Buffalo. Figure 4 shows the general pattern of traffic jam pressure related to five major evacuation routes. The size of the sinks that are represented by green dot symbols on Figure 4 depicts the differentiation of the pressure on the routes; the larger the size of the symbol at a sink, the higher the traffic jam pressure.

Main Street District

The most vulnerable evacuation route is the Main Street evacuation district. A total of 15,970 vehicles were accumulated on the route in this evacuation simulation Figure 5 shows the upstream accumulation, and Figure 6 shows the vulnerability intensity of vehicles per lane for the evacuation route. The traffic is intense starting from Woodlawn Road (Figure 6). The length of the Main Street is highly vulnerable from Downtown Buffalo to the boundary of the city limit just past the University at Buffalo south campus.

Kensington Expressway District

The second most vulnerable district is the Kensington Expressway – Highway 33 egress district. The Kensington Expressway was recently renamed from Downtown Buffalo to the city boundary as the Martin Luther King Jr. Expressway (Fairbanks, 2003). A total of 15,301 vehicles accumulated on this route in the model simulation (Figure 7). The traffic intensifies as one travels along Bailey Avenue and Grider Street and continue the length of the Kensington Expressway (Figure 8). The evacuation route follows the Kensington Expressway from where it begins at Elm Street in Downtown Buffalo to the city boundary at Eggert Road in Cheektowaga.

Interstate 190 North District

The third least vulnerable evacuation route is the Interstate 190 North bound. A total of 11,763 vehicles were accumulated on this route. Figure 9 shows the upstream accumulation, and Figure 10 shows the vulnerability intensity of vehicles per lane for the evacuation route. The traffic intensifies as you travel along Hertel Avenue and continue the length of Interstate 190 North. The evacuation route also follows Niagara Street or the Scajaquada Expressway to the Interstate 190 North to the city limit into the Town of Tonawanda.

Interstate 190 South District

The second least vulnerable district is the Interstate 190 South bound. A total of 9,961 vehicles accumulated in the model simulation. Figure 11 shows the upstream accumulation, and Figure 12 shows the vulnerability intensity of vehicles per lane for the evacuation route. The traffic intensity increases on the route follows Bailey Avenue to Ogden Street to enter the Interstate 190 South at Exit 1 (South Ogden Street). The traffic also jams on Seneca Street as well as the length of the Interstate 190 South.

Skyway District

The least vulnerable evacuation district is the Buffalo Skyway / Lakeshore Complex egress district. A total of 4,519 vehicles accumulated (Figure 13). This area is an old industrial region that is comprises of a large amount of vacant land along the waterfront and Fuhrmann Boulevard, including the vacant land within the Tifft Farms Nature Preserve. The simulated evacuation traffic intensifies as you continue along Tifft Street before reaching Route 5 Buffalo Skyway / Lakeshore Complex and continue along the Lakeshore Complex to the Father Baker Memorial Bridge out of the city into Lackawanna (Figure 14). This intensity is caused by the pockets of high population density in South Buffalo and the fact that Tifft Street is only one lane until shortly before reaching Route 5.

Residential and Work Population Evacuation

Since residential population does not reflect the addition of working population during a typical working day, a simulation based on estimated day time population increase in downtown Buffalo was conducted. A total of 50,000 persons who drive from suburban towns to the City of Buffalo, being either employed in downtown or seeking higher education there, on any given weekday were estimated based on previous studies (e.g., Collison, 2001; Hickey, 2001). The simulation result of 10,000 more vehicles is shown in Figure 15. The 10,000 vehicles were split between Interstate 190 North bound, Interstate 190 South bound, and the Buffalo Skyway / Lakeshore Complex – Route 5 equally owing to the fact that these three routes are easy to access from the downtown Central Business District (CBD).

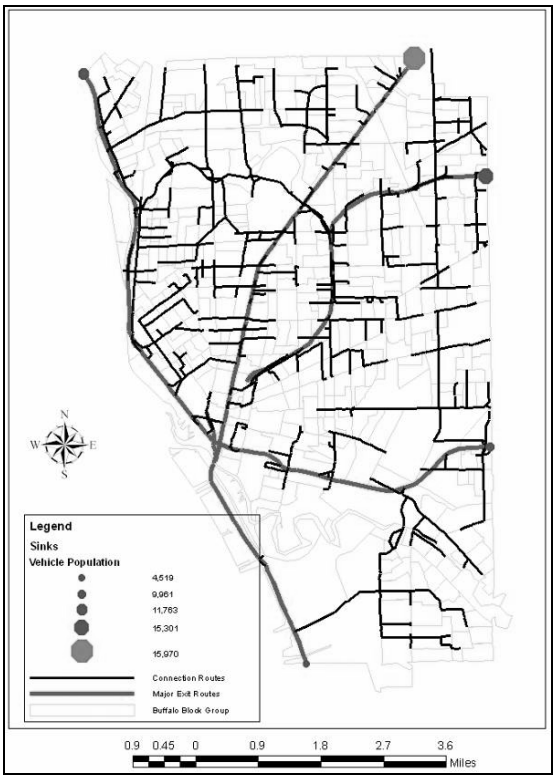

Figure 4. Sink Size of Vehicle Population

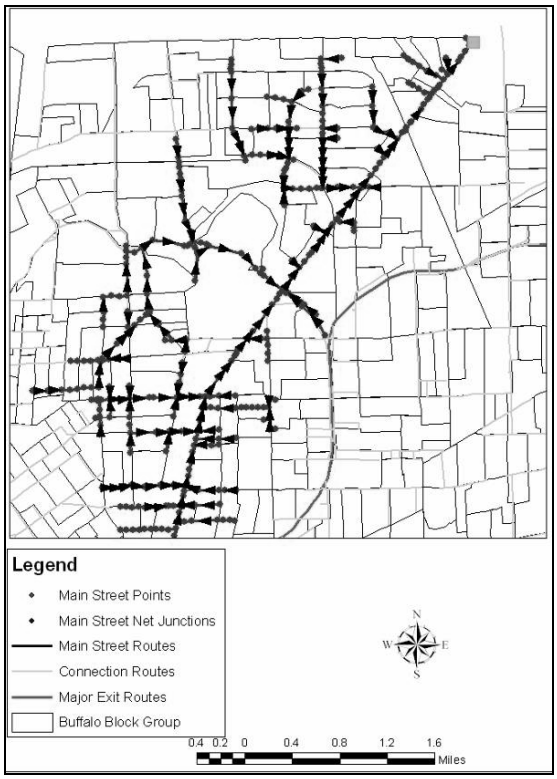

Figure 5. Main Street Evacuation Route Map

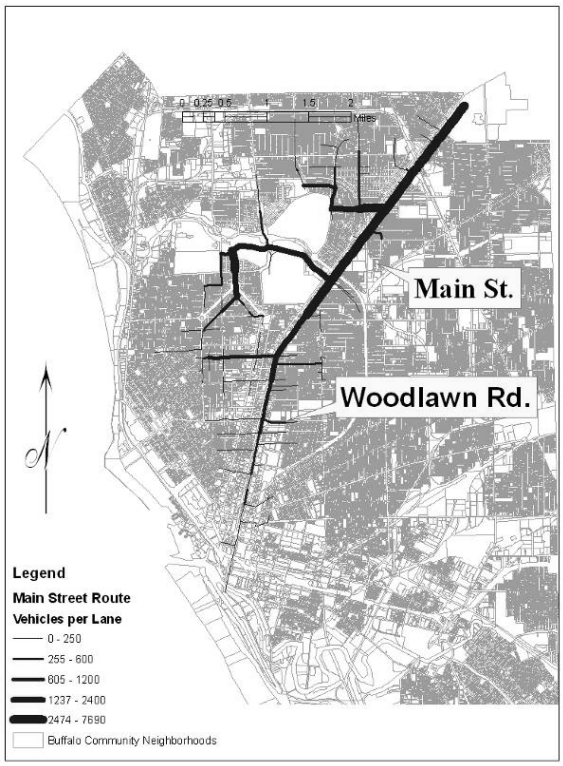

Figure 6. Main Street Evacuation Vulnerability Intensity

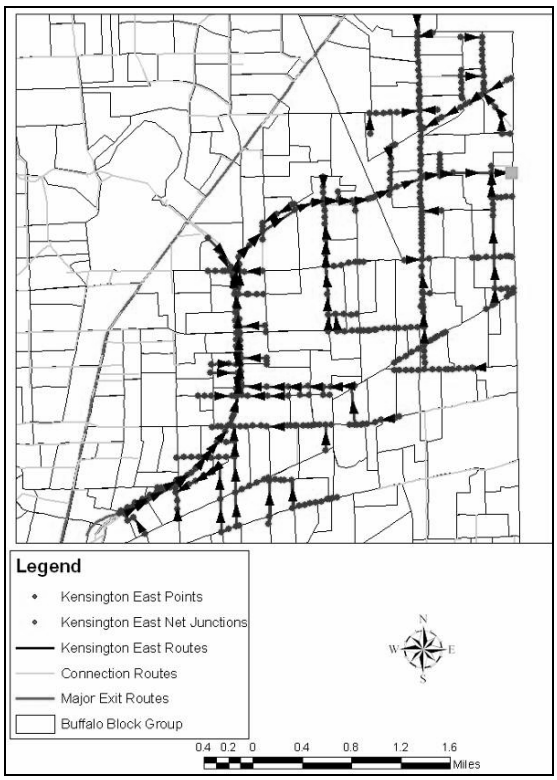

Figure 7. Kensington Expressway Evacuation Route Map

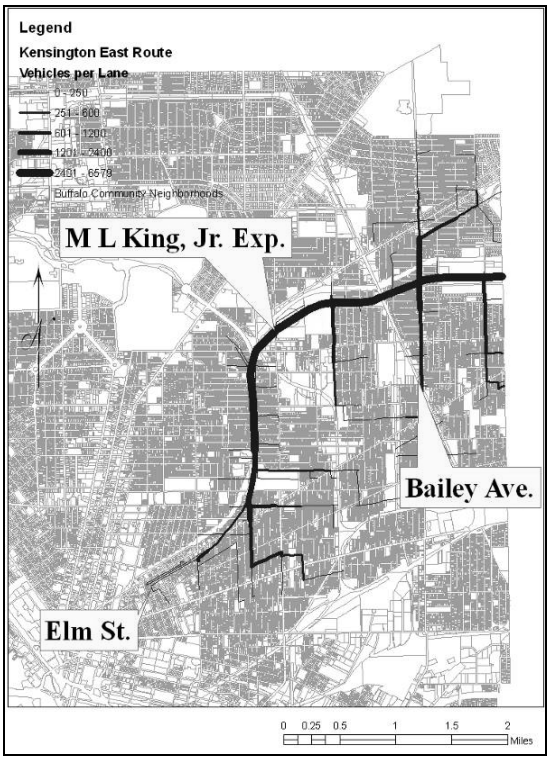

Figure 8. Kensington Expressway East Evacuation Vulnerability Intensity

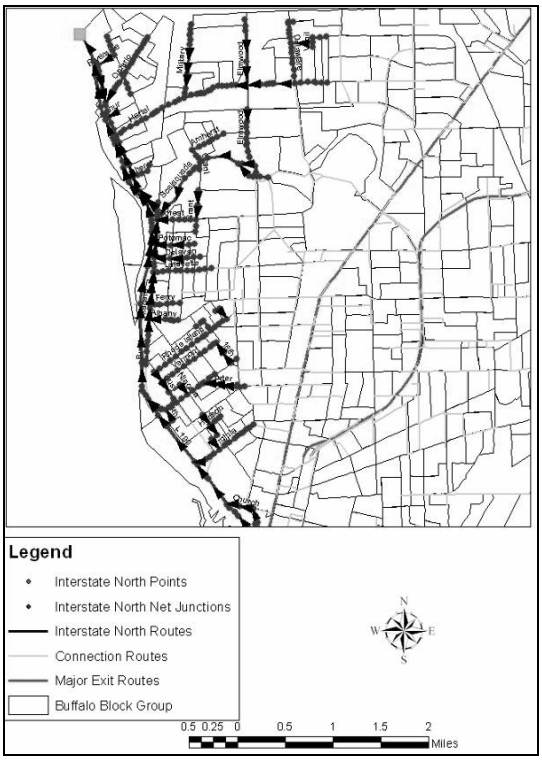

Figure 9. Interstate 190 North Evacuation Route Map

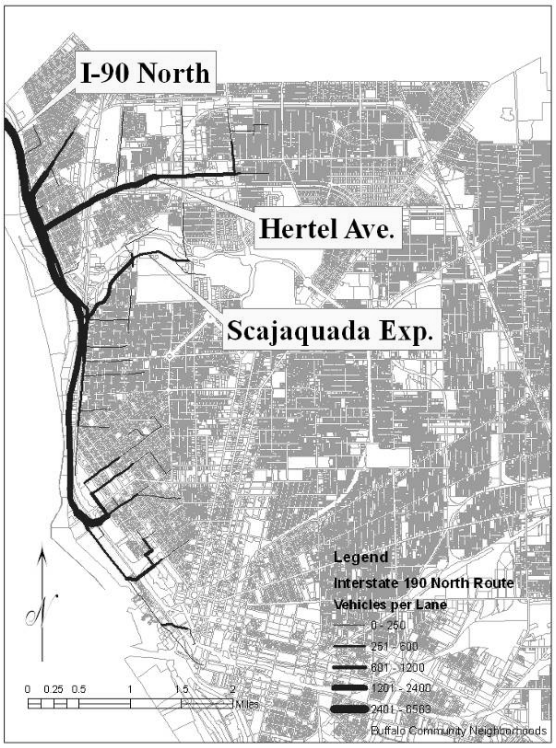

Figure 10. Interstate 190 North Evacuation Vulnerability Intensity

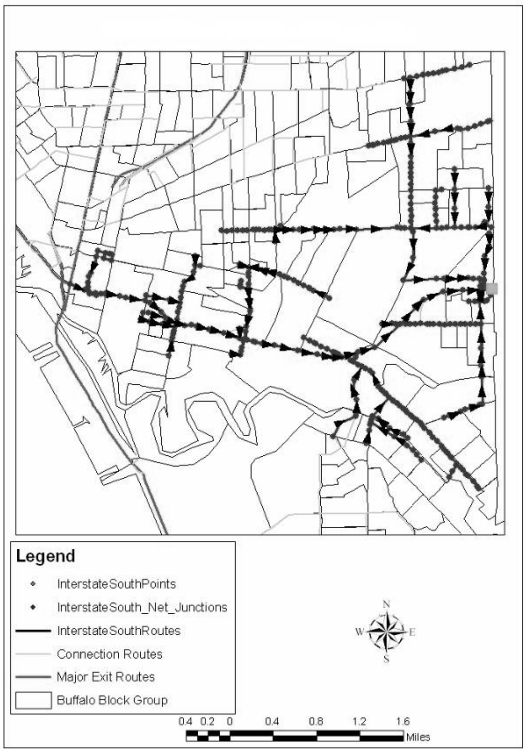

Figure 11. Interstate 190 South Evacuation Route Map

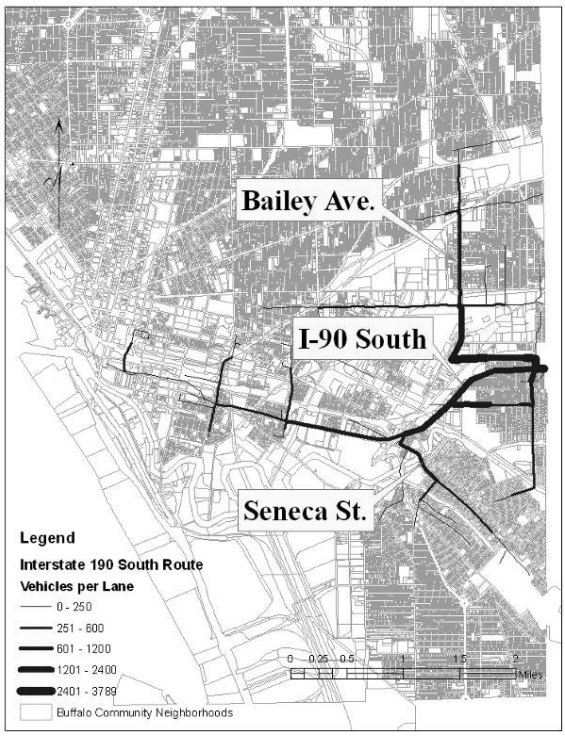

Figure 12. Interstate 190 South Evacuation Vulnerability Intensity

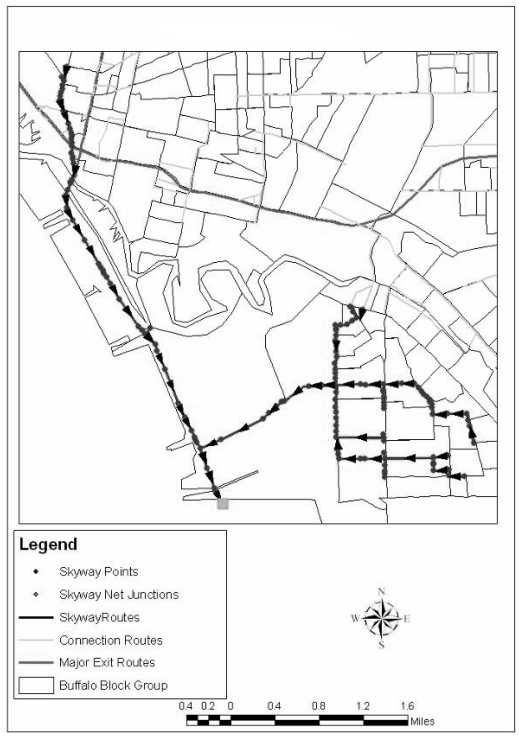

Figure 13. Skyway Evacuation Route Map

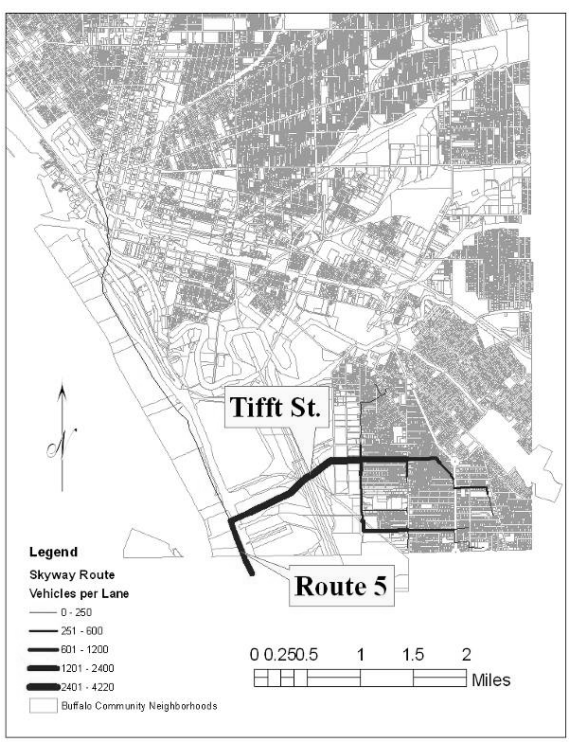

Figure 14. Skyway Evacuation Route Vulnerability Intensity

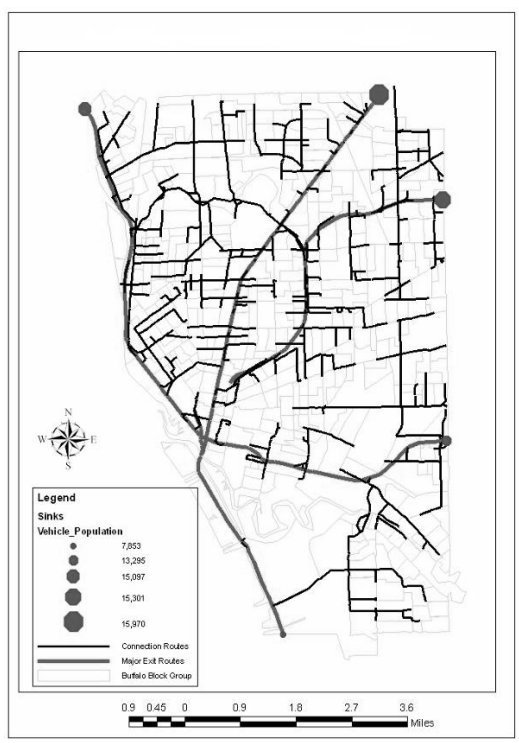

Figure 15. Vehicle Population Daytime Sink Map

In comparison with Figure 4, Figure 15 indicates that daytime population addition does not affect the rank of the evacuation vulnerability among the five major egress routes. Main Street is still the most vulnerable evacuation route in this case, although the traffic jam intensities increased among the three least vulnerable routes. The results suggest that the spatial pattern of traffic congestion affecting the five major evacuation routes exists in either day time or night time. If the working people in downtown select Route 33 during the day time evacuation, the congestion will be drastically increased.

DISCUSSION AND CONCLUSION

In summary this study modeled and visualized the traffic jam hot spots using a distributed geometric network model in ArcGIS. The model can simulate in detail the vehicle accumulations on each of the street edges or intersection junctions during an evacuation event. This can provide government officials of emergency management a useful utility during a hazardous event for effective evacuations. However, several constraints exist in modeling the vehicle population and traffic jams in a distributed network model. First, the accuracy of population distribution during the day and night is the key factor of model prediction of traffic jam hot spots. More accurate population distribution data is needed for the modeling, simulation, and predictions. Second, the Network Analyst tools in ArcGIS need to be improved in order to fulfill the needs of simulated traffic jams on the street and roadway network. Some of the rules established in the network tool sets are too specific. The software engineers of ArcGIS need to understand that geometric network model design must have two levels of controls or rules to accommodate all the different possible usages. One is the general controls and the other should be geared to specific applications either a pipeline or a street network, or a river network. Future studies need to either develop more analytical tools of the geometric network model, or select a specific GIS based transportation software geared to network analysis.

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