A GIS-Based Football Stadium Evacuation Model

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The U.S. Department of Homeland Security (DHS) has identified sports stadiums as part of the nation's critical infrastructure and potential terrorist targets. Therefore, evacuation planning and simulation have been identified as athletic event security best practices and standards. In this study, a Geographic Information System (GIS) based macro-simulation model was developed to compute evacuation time for the University of Southern Mississippi's football stadium in the event of a human-made hazard. Although complex evacuation models exist, the purpose of this study was to develop a prototype GIS-based model that can be used as a training and pre-game preparation tool by local emergency personnel with access to a GIS-software rather than an expensive and proprietary evacuation model requiring skilled professionals. As per the model, the maximum and average evacuation times for all fans to exit the stadium and travel off campus were 4.1 hours and 2.1 hours respectively.

El Departamento de Seguridad Doméstica de los EE.UU. (DHS) ha identificado estadios deportivos como parte de la infraestructura crítica de la nación y como potenciales blancos terroristas. Por lo tanto, la planificación y simulacros de evacuación han sido identificados como prácticas y estándares de seguridad en eventos atléticos. En este estudio, un modelo de macro-simulación basado en los Sistemas de Información Geográfica (SIG) fue desarrollado para calcular tiempo de evacuación para el estadio de fútbol de la Universidad del Sur de Mississippi, en el evento de una amenaza provocada por el ser humano. Aunque existen modelos de evacuación complejos, el propósito de este estudio fue el desarrollar un modelo prototipo basado en los SIG que pueda ser utilizado como herramienta de entrenamiento y de preparación antes de los juegos por el personal local de emergencias con acceso a programas de SIG, en vez de un modelo de evacuación costoso que requiere profesionales adiestrados. En cuanto al modelo, los tiempos de evacuación máximos y promedios para que todos los aficionados abandonen el estadio y se desplacen fuera del campus fue de 4.1 horas y 2.1 horas respectivamente.

KEY WORDS: GIS; evacuation modeling; football stadium; evacuation time; network analysis

PALABRAS CLAVES: SIG; modelos de evacuación; estadios fútbol; tiempo de evacuación; análisis de redes

INTRODUCTION

The estimated value of the U.S. sports industry in 2009 was $410.6 billion (Plunkett Research, Ltd 2008). Fan attendance at football games sanctioned by the National Collegiate Athletic Association (NCAA) was a record-high 48,839,003 in 2008, despite a decline in the national economy (Johnson 2009). Because watching football is a popular, capitalist, and internationally visible part of American culture, sports stadiums are possible terrorist targets (Hurst et al. 2003). A terrorist attack at a football game could have long-term social, psychological, and economic impacts (Sauter and Carafano 2005; Biringer et al. 2007; Hall et al. 2007; Hall et al. 2008). Ed Worthington, the former Director of the Mississippi Office of Homeland Security, once said, "Sporting events are perfect targets because of the number of people amassed in a relatively small space, and in any nation where sports are held in such high regard, an attack on any scale would likely grab national or even international attention" (Hall et al. 2007). Therefore, evacuation planning and simulation have been identified as athletic event security best practices and standards (Hall et al. 2007; Hall et al. 2008).

The purpose of this study was to develop a prototype Geographic Information System (GIS)-based evacuation model for M. M. Roberts Stadium on the Hattiesburg campus of the University of Southern Mississippi (USM) that can be used by emergency responders as a potential training and pre-game preparation tool. The major objectives of this study were to: (1) Identify the number of evacuees and their potential origins and destinations; (2) Identify evacuation routes connecting origins and destinations based on shortest travel time; and (3) Compute the total evacuation time of the stadium starting when the evacuation order is issued and ending when the last evacuee exits the evacuation zone (Figure 1).

BACKGROUND

Historically, sports stadiums have been potential targets for terrorist attacks. Well-known examples include terrorist attacks at the 1972, 1996, 2000, 2004, and 2006 Olympic Games (Varouhakis 2004; Johnson 2008a, 2008b), and bomb and explosive threats, and terrorist attacks at football, basketball, and cricket competitions in 2003, 2005, 2006, and 2009, respectively (ESPN 2003, 2005, 2006; Sports Illustrated 2003; USA Today 2003, 2005; CNN 2009). Because terrorist groups intend to maximize casualties and receive publicity for their causes (Kennedy 2006; Biringer et al. 2007), computer-based training, modeling and simulation, and emergency management have been considered a part of evacuation planning and stadium security management standards that sports stadiums and other such venues should address to ensure safety and security (Hall 2006; U.S. Department of Homeland Security 2009).

Evacuation modeling started in 1942 with the Cocoanut Grove nightclub fire which killed 492 people. However, the Three-Mile Island accident of 1979 led to ground breaking works in this field. Since then, extensive studies have been conducted in evacuation modeling both in the context of human-made and natural hazards. The most common metric of an evacuation model is evacuation time estimation (time required by occupants of an emergency planning zone (EPZ) to exit the zone). A number of models have been developed over the years to estimate travel

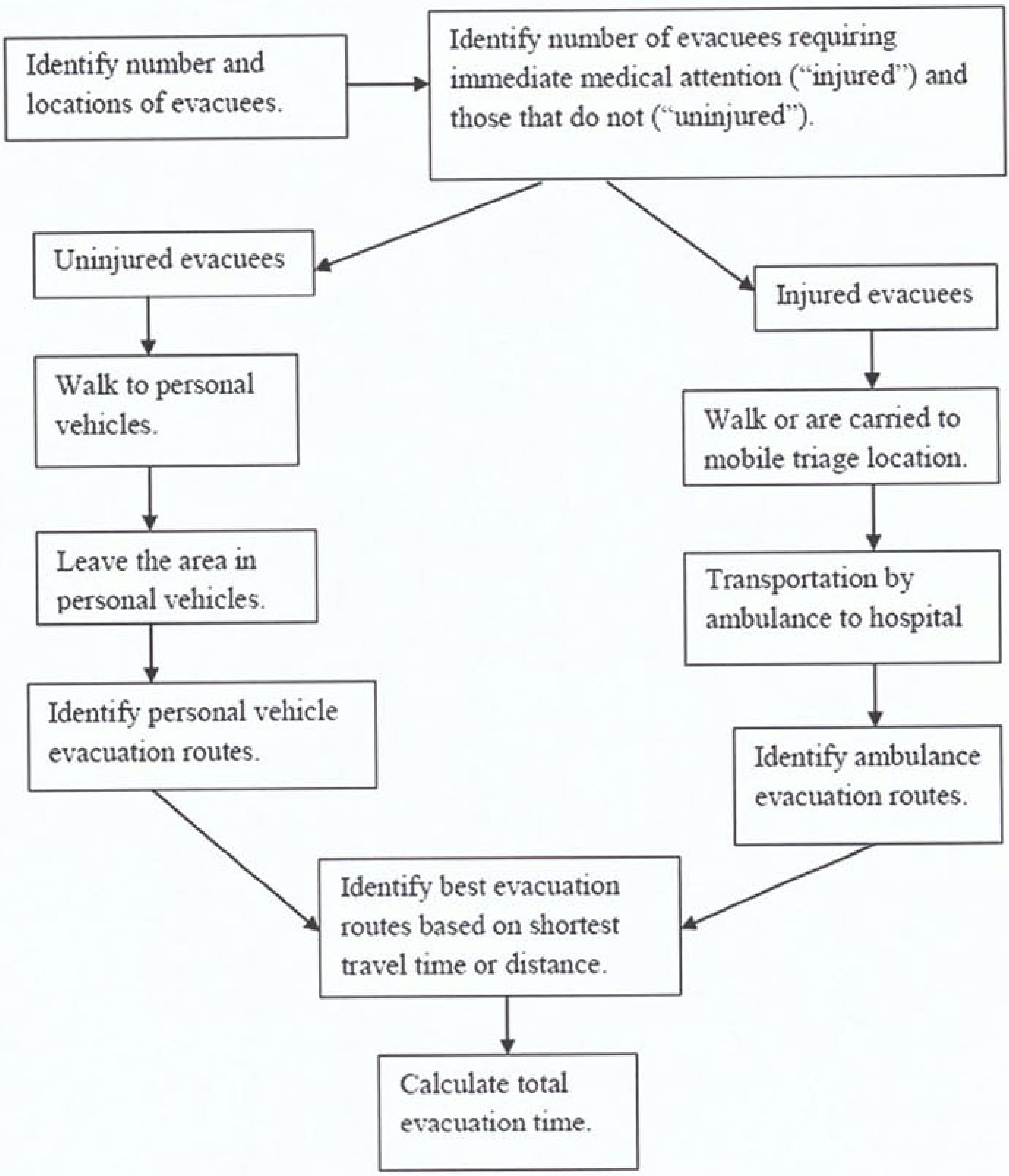

Figure 1. Evacuation model flow diagram.

time for different segments of an evacuation, starting from the time required by officials to give the evacuation warning order to final evacuation of the impacted population from the EPZ (Urbanik 2000; Lindell and Prater 2007).

Depending upon the representation of pedestrian evacuee behavior, evacuation models are classified as flow-based, cellular automata, and agent-based models (Fang et al. 2003; Lo et al. 2004; Santos and Aguirre 2004). Flow-based models represent people as a continuous stream that moves from one part of a building or structure to another until it reaches an exit (Fahy 1994; Thompson and Marchant 1995a, 1995b; Fang et al. 2003; Santos and Aguirre 2004). Cellular automata models consider people as individuals who move from room to room or section to section until an exit is reached. Each movement occurs with the passage of a specified amount of time (e.g. every five seconds) (Santos and Aguirre 2004; Banerjee et al. 2008). Agent-based models depict evacuees as individuals with their own attributes (e.g. walking speed, body size, body shape, proximity to other people, health conditions) that interact with other evacuees and their surroundings as they move towards an exit (Galea and Galparsoro 1994; Batty et al. 2003; Fang et al. 2003; Santos and Aguirre 2004; Banerjee et al. 2008). Due to their intricacy and level of detail, cellular automata and agent-based models are useful when modeling smaller numbers of evacuees leaving complex structures with multiple rooms, floors, and convoluted corridors (Fang et al. 2003; Santos and Aguirre 2004; Banerjee et al. 2008). For evacuation scenarios involving large numbers of people or high density areas where crowds behave more as cohesive units, cellular automata or agent-based models are difficult, if not impossible, to implement (Fahy 1994; Fang et al. 2003).

Evacuation models dealing with vehicular evacuation can be categorized into macro-simulation, meso-simulation, and micro-simulation models. These models account for traffic conditions and traffic process, and require specific input parameters, such as origin and destination of evacuees, number of evacuees, and road networks connecting origin to destination.

With macro-simulation, traffic is modeled as a continuous stream or flow along a road network (De Silva and Eglese 2000; Cova and Johnson 2002; Georgiadou et al. 2007; Chen 2008). This type of model is most useful when determining the time required for road networks to be clear of evacuating vehicles (Sheffi et al. 1982; Hobeika and Jamei 1985; Han 1989; Tufecki and Kisko 1991; Hobeika et al. 1994; Cova and Johnson 2003; Pal et al. 2003). In micro-simulation models, traffic is represented as individual vehicles with their own attributes (e.g., speed, braking behavior, turning behavior) that interact with other vehicles and roads on which they are traveling (De Silva and Eglese 2000; Cova and Johnson 2002; Georgiadou et al. 2007; Chen 2008; Chen and Zhan 2008). Microsimulation models are useful when examining individual driver behaviors and their effects on evacuation time. In meso-simulation, traffic is represented as discrete groups of vehicles with assigned group attributes (De Silva and Eglese 2000; Georgiadou et al. 2007). These models are rarely used because putting vehicles in orderly, logical, and meaningful groups during a possibly disorderly evacuation is unrealistic and difficult (De Silva and Eglese 2000; Georgiadou et al. 2007).

Because modeling individual driver behavior and traffic conditions is computationally complex, over the years, evacuation models, such as the Mass Evacuation Computer Simulation (MASSVAC) (Hobeika and Jamei 1985), the Regional Evacuation Modeling System (REMS) (Tufecki and Kisko 1991), the Transportation Decision Support System (TEDSS) (Hobeika et al. 1994), NETVACI (Sheffi et al. 1982), and the Transportation Evacuation System (TEVACS) (Han 1989) have been developed by computer scientists and civil engineers. These models also laid the groundwork for later models that used GIS (e.g. the Oak Ridge Evacuation Modeling System (OREMS)) and proprietary software packages calibrated for individual studies (Sheffi et al. 1982; Hobeika and Jamei 1985; Han 1989; Tufecki and Kisko 1991; Hobeika 1994; Yamada 1996; Jha et al. 2004; Theodoulou and Wolshon 2004; Chen et al. 2006; Chen 2008; Chen and Zhan 2008).

Cova and Johnson (2002) used a commercial micro-simulation model linked to a GIS, and De Silva and Eglese (2000) created a comprehensive evacuation decision support system by combining a GIS and a micro-simulation software. Pal et al. (2003) created a macro-simulation evacuation model for Baldwin and Mobile Counties in Alabama by combining GIS and the OREMS. Cova and Johnson (2003) used a macro-simulation model to simulate evacuation of Salt Lake City, Utah and compute evacuation time. The authors compared the results obtained from the macro-simulation model to a micro-simulation model and manual calculations, which revealed that all three methods produced evacuation times within 30 seconds of each other.

Cova and Johnson's (2003) study indicated that existing macro-simulation and micro-simulation models do not always perform significantly different. One reason for this is that all of the aforementioned models (MASSVAC, TEVACS, OREMS, etc.) employ algorithms widely used to determine shortest routes: Dijkstra, Out of Kilter, Minimum Cost, K-Shortest Path and Lane-based routing. Nonetheless, a major advantage of these models is their ability to determine evacuation routes, evacuation time, and possible bottlenecks from an event location based on traffic process and condition, and evacuee behavior.

Because these models account for a number of input parameters, they are both data and computationally intensive. Being proprietary in nature, these models/software packages are expensive and require skilled professionals. They also do not always produce spatially-referenced output that can be visually represented as a map. Finally, controlling all variables, parameters, and assumptions of evacuation models is not always possible or documented, which in turn can introduce uncertainties into the final outcomes.

Because most of the data required for emergency management is spatial in nature, GIS is used for gathering, organizing, and analyzing data sets as well as for data dissemination, visualization, and training (Cova 1999; Johnson 1999; Cutter 2003). ESRI's GIS software (ArcGIS) is widely used by county, state and Federal emergency management agencies in the United States. Even the HAZUS-MH (Hazards of US-MultiHazard), a loss estimation tool developed by the Federal Emergency Management Agency (FEMA) is integrated with ArcGIS. A GIS also produces spatially-referenced data corresponding to real-world locations and accounts for the earth's shape, such that estimated distance in a specific direction is much more precise and accurate. Non-spatial referenced products created by many evacuation models do not account for the earth's shape, and correspond to relative location, which can lead to inaccurate distance and evacuation time computation.

In this study, a GIS-based evacuation model was developed for the local emergency personnel who have access to ESRI's GIS software, but not to proprietary evacuation models due to lack of funding and skilled professionals.

METHODOLOGY

The study site, M. M. Roberts Stadium, a 33,000-seat football stadium is located in the Hattiesburg campus of The University of Southern Mississippi (USM) in Forrest County, Mississippi (Figure 2). While this specific stadium may not be a terrorist target in comparison to larger, more well-known locations, it operates the same way as larger stadiums, information about it is readily available, and it is familiar to DHS. Thus, the GIS-based macro-simulation evacuation model prototype developed for this stadium to determine network clearance time can be applied to other stadiums of similar size in the U.S. Emergency response personnel from USM's Athletic Department, campus and local law enforcement agencies, hospitals, and the city's transportation office were interviewed to model the actual sequence of events that would occur during the stadium's evacuation.

The data layers were obtained from the Mississippi Department of Transportation (MDOT) (road layers, traffic volume and speed limit), USM's Department of Geography and Geology (campus buildings), United States Geographic Survey (3-meter resolution Digital Elevation Model), and Mississippi GIS Clearinghouse (hospital layer, 2007 1-meter resolution image of Forrest County). All layers were converted to North American Datum 1983, Universal Transverse Mercator, Zone 16 North projection. All raster layers were created at 1.5 m x 1.5 m spatial resolution.

Origins, Destinations and Number of Evacuees

In this study, a two-stage evacuation model was implemented. In the first-stage, the stadium was used as the origin from where the audience must evacuate in the event of a human-made hazard. Because this model was developed for the worst-case scenario, the maximum stadium capacity (33,000 seats) was used as the total number of evacuees. To compute travel time within the stadium from different sitting areas to exit corridors, an audience layer was created by evenly distributing students (4,148) and non-students (28,852) within student and non-student sections of the stadium. The potential destinations in this stage were parking lots for uninjured evacuees and mobile triage locations for injured evacuees.

The second-stage of the model included the evacuation of the stadium audience from parking lots (origin for uninjured evacuees) and mobile triage locations (origin for injured evacuees) to their potential final destinations, which included nearby road networks and road intersections.

Based on a recent study conducted by the Oak Ridge National Laboratory (ORNL), we estimated that 88 percent of USM fans use personal vehicles, 8 percent walk, and 4 percent use other modes of transportation to travel to and from the stadium (Jones et al. 2009). In the second stage, 29,040 people (88 percent of 33,000) were used to compute evacuation time. Individuals assumed to leave the area on foot or by other non-specified modes of transportation during the evacuation were excluded from the model due to lack of information about their transportation methods.

According to USM's Ticket Office, there were 2,500 season ticket holders for the stadium and 11,000 season tickets in 2009. Because the number of occupants per vehicle travelling to games is un-

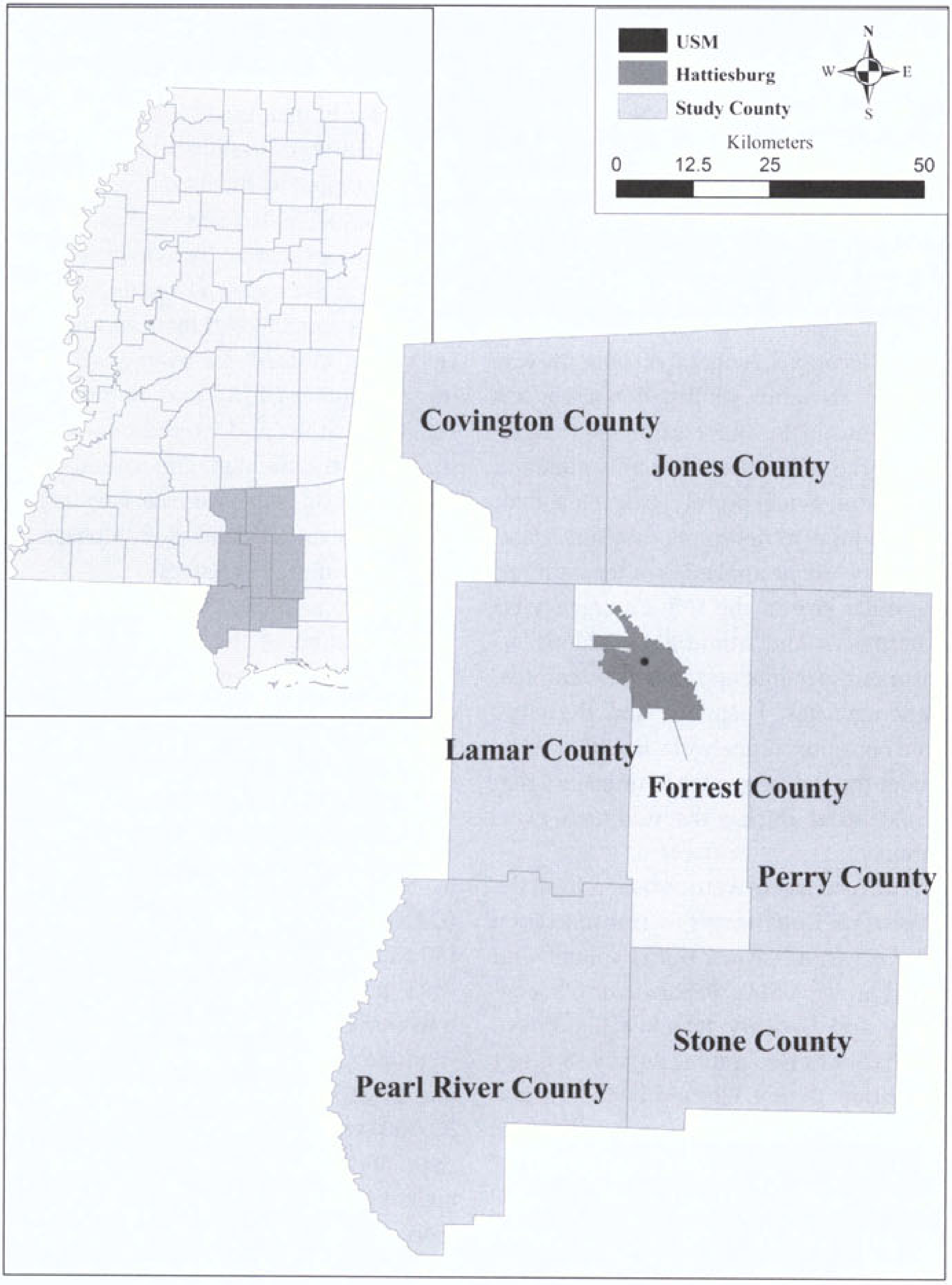

Figure 2. M. M. Roberts Stadium, University of Southern Mississippi; Hattiesburg, Mississippi.

known, in this study, the number of season tickets (11,000) was divided by the number of season ticket holders (2,500), which yielded approximately four. Four people per vehicle was used to compute parking space for 29,040 evacuees, which resulted in 7,260 vehicles. According to the USM's Ticket Office, 2,786 vehicles belonging to season ticket-holders have reserved spaces and non-season ticket holders park in any available designated parking location within one half of a mile from the stadium. Using this information, additional parking spaces were identified within a half-mile radius of the stadium with help of the USM's Ticket Office personnel for the 4,474 vehicles.

For uninjured evacuees, destinations include parking lots followed by the closest intersections to main roads that border the USM campus (Kittrell and Thompson 2009). Based on our interviews with emergency personnel, injured evacuees, depending upon their extent of injury, would either walk or be carried to a mobile triage location (first destination) before they are moved by ambulance to one of the two hospitals (second destination).

Mobile triage locations should be sited on large, flat, empty areas with entrances and exits large enough to accommodate ambulances and emergency responders, and within 0.3 miles (0.5 km) of the stadium for easy access of wounded evacuees (Carter 2009; Kittrell and Thompson 2009). Based on these criteria, Football Practice Field, Pride Field, and Intramural Fields (Figure 3) were identified as potential triage locations surrounding the stadium. These locations had a slope less than 20 percent, were within 0.3 miles (0.5 km) of the stadium, and did not house any campus buildings.

Using a Global Positioning System and existing 2007 satellite imagery of the university (1-meter resolution), a sidewalk layer was created to connect stadium exits to mobile triage location and parking lots. Road networks for Forrest County were obtained from MDOT.

Evacuation Time Calculations

Before computing travel time within the stadium, evacuees were evenly distributed among the 16 exit corridors (Equation 1). A three-dimensional computer model of the stadium built by USM's Schools of Computing and Construction revealed that the maximum capacity of a corridor exit was 25 people per second. Using Equation 2, evacuees in each corridor were divided into groups of 25 people. Travel time for each exit corridor was calculated by dividing the maximum and average corridor lengths by the average human walking speed of 1.5 meters per second (Daamen and Hoogendoorn 2003) (Equation 3). Finally, by multiplying the number of evacuee groups with travel time through corridors, the evacuation time for the stadium was determined (Equation 4). Arc GIS's Network Analyst (an extension of ArcGIS that has functionalities to determine the shortest route, closest facilities, and service areas based on travel time and distance) was also used to estimate maximum and average evacuation times within the stadium.

$$pop\_corr = total\_pop / num\_corr \quad (1)$$

$$evac\_group = pop\_corr / max\_cap \quad (2)$$

$$corr\_time = corr\_length / walk\_speed \quad (3)$$

$$stad\_evac\_time = evac\_group * corr\_time \quad (4)$$

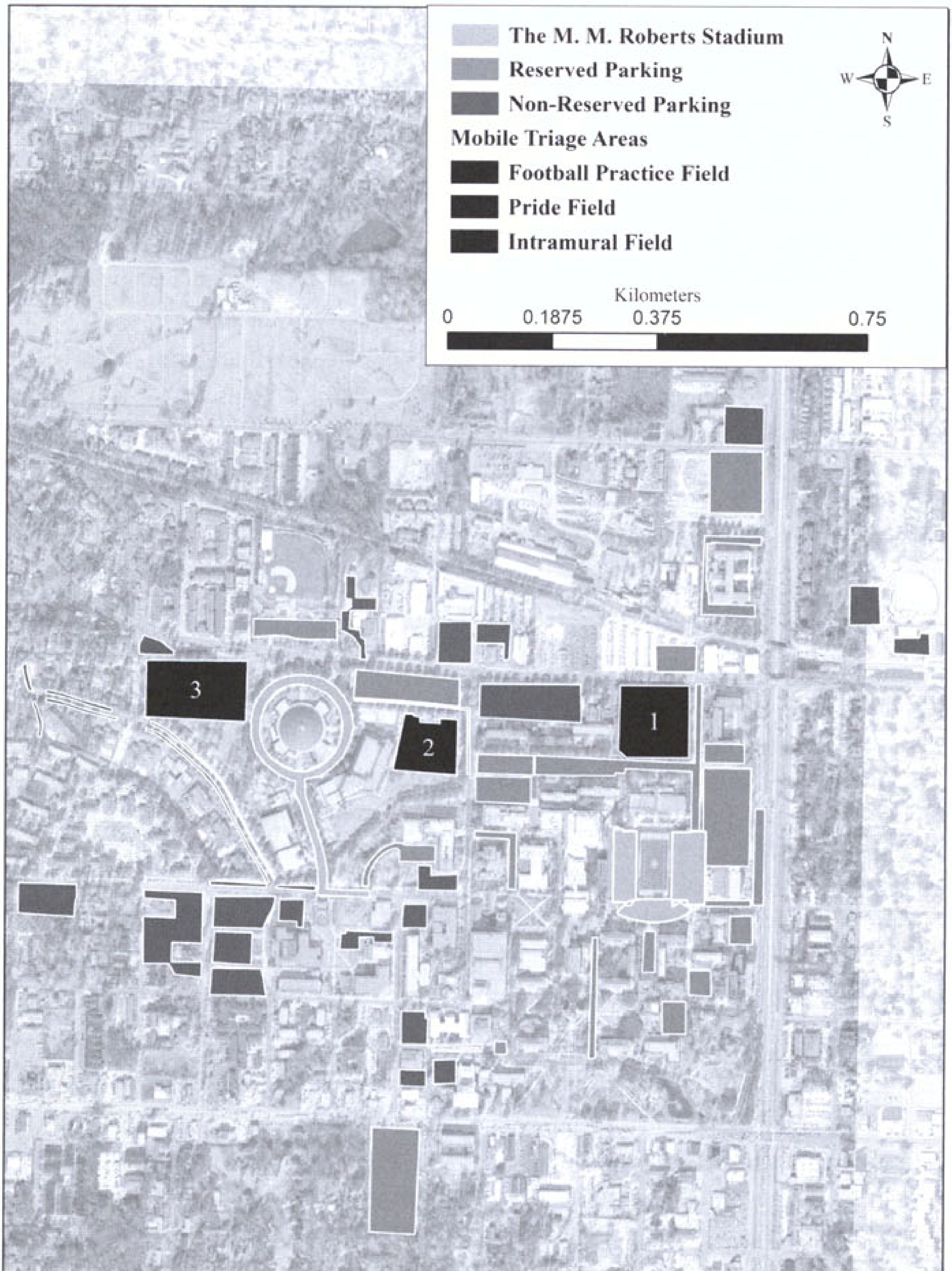

Figure 3. Location of mobile triages and parking lots.

Where *pop_corr* = number of evacuees per exit corridor, *total_pop* = maximum stadium population, *num_corr* = number of exit corridors, *evac_group* = number of groups of evacuees per exit corridor, *max_cap* = maximum capacity of corridor exits (i.e. in this case 25 people per second), *corr_time* = travel time to walk the longest or average corridor length in the stadium, *corr_length* = longest or average stadium exit corridor length, *walk_speed* = average adult human walking speed, and *stad_evac_time* = time required for all evacuees to exit the stadium based on maximum or average corridor length.

Because the path that evacuees or emergency personnel might take from the stadium exits to nearby mobile triage locations is unknown, it was assumed that evacuees will follow a straight-line route from exits to triage locations. With this assumption, straight-line distance was computed from 16 stadium corridor exits to three mobile triage locations. From all the distance measurements, maximum and average distances from stadium exits to triage locations were computed and then divided by average human walking speed of 1.5 meters per second (Daamen and Hoogendoorn 2003) to calculate evacuation time (Equation 5).

$$triage\_time = stad\_triage\_dist / walk\_speed \qquad (5)$$

Where *triage_time* = maximum/average evacuation time for injured evacuees to move from the stadium corridor exits to a triage location and *stad_triage_dist* = the maximum/average distance from a stadium corridor exit to the closest mobile triage area.

Using Network Analyst, the fastest routes from triage locations to nearby hospitals were determined. Local area knowledge of ambulance service was also used to determine travel routes from the stadium to nearby hospitals. The length of each road segment along the route determined by ambulance service was divided by the speed limit for each segment to determine travel time. All segment travel times were summed to estimate total travel time for an ambulance along a preferred ambulance route from a mobile triage location to a hospital (Equation 6).

The local ambulance service could quickly deploy 10 ambulances, each with a capacity of two (2) injured evacuees to mobile triages (Carter 2009). Therefore, the total number of injured evacuees was divided by two to determine number of required ambulances. Since the amount of time required to treat and load patients into an ambulance depends upon the extent of injuries, it was assumed that all 10 ambulances will leave simultaneously as a group. Therefore, the number of required ambulances was divided by 10 and multiplied by the time calculated in Equation 6. Each time a group of 10 (or fewer) ambulances returned from a hospital to a mobile triage area to pick up additional injured evacuees, the value from Equation 6 was added to the travel time (Equation 7). This enabled estimating total time required for moving injured evacuees from triages to hospitals.

$$hosp\_time = \mathrm{Sum}[(length_1 / speed_1) + (length_2 / speed_2) + \ldots + (length_n / speed_n) \qquad (6)$$

$$amb\_time = (inj\_evac / inj\_evac\_amb / num\_amb * hosp\_time) + [(inj\_evac / inj\_evac\_amb / num\_amb - 1]) * hosp\_time \qquad (7)$$

Where *hosp_time* = travel time from each mobile triage area to the hospital, $length_1 \ldots\ldots length_n$ = length of each road segment in the respective mobile triage route, $speed_1 \ldots\ldots speed_n$ = speed limit of each road segment in the respective mobile triage route, n = number of road segments in the respective mobile triage route, *amb_time* = travel time from the mobile triage area to the hospital based on the number of injured evacuees, *inj_evac* = number of injured evacuees, *inj_evac_amb* = number of injured evacuees per ambulance (constant value of 2 in this model), and *num_amb* = number of available ambulances (constant value of 10 in this model).

Instead of computing distance from 16 stadium corridor exits to 54 parking lots, the distance from the center of the stadium to each parking lot was measured to reduce the number of measurements. Uninjured evacuees were evenly divided among the 16 corridor exits and assumed to evacuate simultaneously. Maximum and average evacuation times for individuals were calculated by using Equation 8. Maximum and average evacuation times for all evacuees in this segment were calculated by dividing the total number of evacuees with the number of stadium exit corridors and multiplying the product by individual maximum and average evacuation times (Equation 9).

$$walk\_time = dist * walk\_speed \qquad (8)$$

$$walk\_park\_time = total\_pop / num\_corr * walk\_time \qquad (9)$$

Where *walk_time* = maximum/ average walking travel time from the center of the stadium to parking lots, *dist* = maximum/ average distance from the center of the stadium to the farthest parking lot, *walk_speed* = average human walking speed (constant 1.5 meters per second), and *walk_park_time* = the time required for uninjured evacuees to walk from the stadium to parking lots.

Vehicles were distributed evenly among the 39 destinations (nearby road intersections) for uninjured evacuees to compute travel time from 54 parking areas to the 39 destinations. Maximum and average travel times of an individual vehicle were used to calculate evacuation time for this segment by using Equation 10. Finally, total evacuation time was determined by summing times associated with: (1) travel in the stadium, (2) uninjured evacuees traveling from stadium exits to their vehicles, (3) uninjured evacuees driving out of the impact zone, (4) injured evacuees being moved from stadium exits to triage centers, and (5) injured evacuees being moved to a hospital by an ambulance. Since the injured and uninjured segments of the evacuation occur simultaneously, the evacuation time for all evacuees will equal whichever is longer. Thus, both maximum and average total evacuation time was calculated using Equations (11) through (13).

$$unin\_drive\_time = num\_veh / num\_dest * trav\_time \qquad (10)$$

$$\text{if } u + d > i + h, TET = s + u + d \qquad (11)$$

$$\text{if } u + d < i + h, TET = s + u + d \qquad (12)$$

$$\text{if } u + d = i + h, TET = s + u + d \text{ or } TET = s + i + h \qquad (13)$$

Where *unin_drive_time* = maximum/ average time required for uninjured evacuees to drive from parking lots to the destination location, *num_veh* = number of evacuating vehicles (7,260 in this model), *num_dest* = the number of uninjured destination locations (39 in this model), *trav*

Table 1. Stadium evacuation time.

Method	Maximum Time (minutes)	Average Time (minutes)
Distance Measuring Tool	50.84	41.94
New Closest Facility	50.16	41.79
Percent Difference	+1.34%	+0.36%

_time = the maximum/average travel time of a vehicle, *TET* = total maximum or average evacuation time, *s* = maximum or average time for all evacuees to exit the stadium, *u* = maximum or average time for uninjured evacuees to walk from the stadium to their vehicles, *d* = maximum or average time for uninjured evacuees to drive out of the impact area, *i* = maximum or average time for injured evacuees to walk or be carried from the stadium to the mobile triage area, and *h* = time for the injured evacuees to move by ambulance to the hospital.

As the model is a prototype, 50 injured evacuees were used in the calculation, which was sufficient for local ambulance service to set up triage locations, and in turn to estimate evacuation time from the stadium. In case of a specific hazard event, a different combination of injured-uninjured evacuee can be used as input in the model to calculate evacuation time.

RESULTS, DISCUSSION AND CONCLUSION

Manual calculation and the Network Analyst resulted in a maximum travel time of 50.84 minutes and 50.16 minutes respectively within the stadium, and an average travel time of 41.94 minutes and 41.79 minutes respectively (Table 1). There was a 1.34 percent difference between the methods for maximum time and a 0.36 percent difference for average time (Table 1).

Of the three mobile triage locations, the Football Practice Field is preferred by ambulance service because of its proximity to the stadium (Carter 2009). The maximum and average travel times of injured evacuees from the stadium to the Football Practice Field were 2.49 minutes and 2.24 minutes respectively (Table 2).

Both the ambulance service and Network Analyst identified Forrest General Hospital as the closest medical facility to the mobile triages. Travel time from mobile triage locations to Forrest General Hospital based on the number of injured evacuees (50), number of evacuees per ambulance (2), and number of ambulances (10) was 8.35 minutes (Table 2). The shortest route (2.37 minutes) was from Pride Field to Forrest General Hospital (Table 3). However, the travel time along US-49 (preferred ambulance routes by ambulance service) from the Football Practice Field had a shorter travel time to Forrest General Hospital (1.67 minutes), rather than Pride Field (Table 3).

Maximum and average travel times from stadium exits to parking lots were found to be 13.1 minutes and 6.2 minutes respectively (Table 2). Using Network Analyst, an average travel time of 1.26 hours and a maximum travel time of 3.0 hours were

Table 2. Total evacuation time along different segments.

Segment	Equations	Maximum Time	Average Time	Standard Deviation
Within stadium	8–14	50.8 min	41.9 min	0.1 min
Injured stadium to triage	15–16	2.5 min	2.2 min	0.4 min
Injured triage to hospital	17–18	8.35 min	8.35 min	n/a
Injured segment sum	*25–27*	*10.9 min*	*10.6 min*	*n/a*
Uninjured stadium to parking	19–22	13.1 min	6.2 min	3.1 min
Uninjured parking to destination	23–24	180.0 min	75.6 min	16.5 min
Uninjured segment sum	*25–27*	*193.1 min*	*81.8 min*	*n/a*
Total time	25–27	4.1 hr	2.1 hr	n/a

estimated from parking lots to destinations (Table 2). The total evacuation time based on maximum segment times was 4.1 hours and based on average segment times was 2.1 hours (Table 2).

Numerous evacuation models have been developed over the years by computer scientists and engineers, as discussed in the Background section of this article. These models account for evacuee behavior unlike the model developed in this case study. Despite being simple in its implementation, our model has a number of advantages over more complex models.

1. The purpose of this study was to develop a prototype GIS-based evacuation model for the local emergency personnel. Unlike the sophisticated and computationally intensive models (discussed earlier) that are expensive and require skilled professionals, our model can be used readily as a training and pre-game preparation tool by local emergency personnel with access to ESRI's ArcGIS because of its *simplicity*.
2. The percentage distribution of injured versus non-injured evacuees is dependent upon the emergency situation. Likewise, the walking speed of 1.5 meters per second that was used in this study might not hold true depending upon the emergency situation. Nevertheless, to address this issue, a *linear programming* approach was used in this study. The linear programs can be altered to account for a different walking speed, and to depict percentage injured-non-injured evacuee distribution, available parking space and number of passengers per vehicle, which in turn will influence final evacuation time.

From an emergency responder's perspective, it is possible to evacuate 29,040 people from the stadium to safety locations, especially nearby intersections/hospitals within 2.1–4.1 hours in case of an emergency. It is possible to evacuate 33,000 people from the stadium within 41–51 minutes. These estimates also indicate that it is possible for emergency per-

Table 3. Hospital travel time: Network Analyst.

Triage Location	Network Analyst Travel Time (minutes)	Preferred Route (US-49) Travel Time (minutes)	Actual Difference (minutes)	Percent Difference
Football Practice Field	2.57	1.67	0.90	35.08%
Pride Field	2.37	2.27	0.11	4.43%
Intramural Fields	3.16	2.93	0.23	0.57%

sonnel to aid injured and uninjured evacuees to evacuate within a reasonable time rather than getting delayed for longer durations. Given its simplicity, ease of deployment in a GIS environment, ability to make modification to different parameters impacting potential evacuation time, and close approximation of evacuation from a stadium in comparison to other models (discussed in the following sections), our model can potentially be used by similar sized university stadiums around the country as a training and evacuation preparation tool for future game events. However, what are the ramifications of the evacuation time in the context of other existing models?

Before answering this question, it is important to examine other informal models applicable to similar situations. SimWalk, a micro-simulation software implements an agent-based model to simulate behavior of individual pedestrian to evaluate security as well as to compute evacuation time (Simwalk 2007). The model was used by the Cartographic Modeling Lab (CML) of University of Pennsylvania to simulate evacuation of about 18,000 people (12,000–13,000 parents, 6,000 students, 70 academic council members, and 75 disabled people) from the Franklin Field stadium during graduation in 2007. The simulated evacuation time changed from 15–16 minutes, which coincided with an evacuation experiment undertaken by the public safety management team for the stadium (Simwalk 2007).

EXODUS is a rule-based, micro-simulation model, which can be used to compute evacuation time and routes from an enclosed space during a fire or toxic gas explosion (FSEG 2011). The software is written in C++ using Object Oriented techniques. The model uses a two-dimensional spatial grid depicting the geometry of a structure, its exits, internal compartments, obstacles, etc. Individuals move from node to node within the grid. Each individual's travel time is computed based on his/her walking speed and distance depending upon his/her attributes (e.g. age, weight, agility, and response time to the event).

Oak Ridge Evacuation Modeling System (OREMS) is a Windows-based software program designed to model vehicular evacuation during an emergency situation (ORNL 2011). The system has a GIS interface and uses ORNL-based Landscan USA (high resolution population database) to determine at-risk population for evacuation time computation.

Simwalk calculated that an audience of 18,000 at a graduation ceremony would evacuate Franklin Field stadium at the University of Pennsylvania in approximately 16 minutes. Using this model, an audience of 33,000 from the M. M. Roberts stadium would evacuate in about 30 minutes. Our modeled evacuation time ranged from 41–51 minutes, about 11–21 minutes more than what Simwalk would have calculated. Unlike graduation, where people are willing to follow protocols, our hazard scenario simulates people who would be confused due to unknown impacts of the event. Audience members, therefore, will evacuate the stadium in a more chaotic fashion, which can and most likely will influence evacuation time. There is also a possibility for certain exits to be closed because of the hazard event, which in turn can increase congestion and bottlenecks in other exits due to increasing audience flow. This might also lead to an increase in evacuation time. Given our model overestimated the evacuation time by only 21 minutes, which potentially could be used by evacuees to exit the area or by emergency personnel to organize the evacuation, it can safely be concluded that this simplified model can be used by local emergency personnel as a training and evacuation plan preparation tool.

Our model, like EXODUS, implements a similar raster-based approach to depict a structure and its exits. However, our model assumes a constant walking speed of 1.5 meters per second, which can be changed using the linear programs provided in the study. From an emergency personnel's perspective, EXODUS is both data and computationally intensive, and requires skilled professionals to operate. Therefore, it is not useful to local emergency personnel who are interested in training to prepare for an emergency situation and want to use ESRI's ArcGIS software.

Though the OREMS software is useful and has a GIS interface, LandScan population data is not freely available to public. Furthermore, the model does not provide the option of using other population distribution layers, for example, the stadium population layer created in this study. Likewise, being proprietary in nature, emergency personnel cannot make any changes to the OREMS software unless they are trained to do so. Our model, on the other hand, can be used freely as a training and preparedness tool with minimal training.

This basic evacuation model showed that it is possible to model evacuation from a football stadium, which involves evacuation within a built environment, on sidewalks, and road networks, using a GIS. Nonetheless, because it is difficult to accurately predict behavior of thousands of people, as this research attempts to do, many potential sources of error exist.

1. Within the stadium, it was assumed that all fans were in their seats when the evacuation order was given, evacuees are evenly distributed among corridor exits, and all evacuees would proceed in an orderly fashion, moving uniformly at 1.5 meters per second.
2. It was assumed that injured evacuees would walk from the stadium to triage centers along sidewalks at a walking speed of 1.5 meters per second. While this might be the case, it is possible for people to walk in other open areas at varying speeds depending upon the extent of their injuries.
3. It was assumed that uninjured evacuees would travel at 1.5 meters per

second and use sidewalks. Although average and maximum travel distances from stadium corridor exits to parking lots were used to compute evacuation time in this model, they might not apply uniformly to all evacuees.

4. Vehicles were evenly distributed among all potential destinations and parking lots. Drivers might choose routes based on their destinations outside campus. Moreover, the University Police Department might alter traffic patterns and speed limits to facilitate the evacuation depending upon the event (Kittrell and Thompson 2009). The assumption that all roads are functional, normal traffic pattern exists, and speed limit is uniform might not hold true for every situation.
5. Vehicles of injured evacuees were not subtracted in the model because of their negligible number. However, the number will be different if injured evacuees represented a greater percent of total stadium population.

Evacuation modeling is one of the DHS's High Priority Technology needs (U.S. Department of Homeland Security 2009). In her keynote address on August 2, 2010, at the National Sports Safety and Security Conference in New Orleans, Louisiana, DHS Secretary Janet Napolitano said, "Terrorism at sporting events is a long-standing risk from Munich [1972 Olympics] to [the] present day." Given this necessity, future research will attempt to account for different combinations of injured-uninjured evacuees. Likewise, agent-based modeling will be used to simulate the behavior of evacuees based on specific attributes, such as panic, refusal to evacuate, age, health condition, gender, and driving behavior, to better determine the accuracy and acceptability of the current model.

ACKNOWLEDGEMENTS

Many thanks to Drs. David Cochran, George Raber, Stacey Hall, and Carl A. Reese for their valuable suggestions. Also, many thanks to Dr. Lou Marciani and the staff at The National Center for Spectator Sport Safety and Security for their much-needed support in completing this research.

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