IDENTIFYING AREAS PRONE TO COMPLICATED EVACUATIONS: AUSTIN, TEXAS

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As urban populations grow, and transportation networks are pushed to their limits, both the potential for disaster and the difficulty of preparing for and responding to crises increase. Among the problems associated with increased urban density is the challenge of evacuating citizens to safety when disaster strikes. Threats of terrorism, chemical spills, fire storms, and the like are not likely to necessitate evacuations of entire cities. Instead, these urban extreme events threaten relatively isolated portions of these spaces. The spatial variation of the urban socio-demographic and infrastructural landscape,

coupled with the wide range and severity of different types of urban hazards, make the comprehensive planning of evacuations of urban areas difficult, if not impossible.

A complicated evacuation occurs in an urban area that, for a variety of reasons, has a significantly slower rate of egress than in surrounding areas. Areas affected by complicated evacuation form the weakest links in an evacuation process. A way to help mitigate the potential effects of complicated evacuation is to identify those areas and populations that are at greatest risk for complicated evacuation (Lu et al. 2005). Armed with this knowledge, emergency planners can prioritize their planning efforts so that the needs of more vulnerable areas are addressed effectively.

This thesis offers a method to identify areas that are vulnerable to complicated evacuations through a system-wide analysis of a transportation network's characteristics and its ability to effectively move people out of harm's way. This method determines the evacuation capability of census block groups through the examination of four variables: (1) bulk lane demand, which compares the number of people in an area to the length of road available to them, (2) intersection occurrence frequency, which reflects the impedance of traffic flow caused by intersections, (3) distance to arterials, which measures the time-cost added by distance and (4) vulnerable facilities, which is a count of people housed in facilities such as hospitals and prisons in an area. The identified areas with potential for complicated evacuation are further evaluated to determine if social injustice is an issue in urban evacuation. Analyses were conducted to examine if minorities, the elderly, and the poor are at a greater risk for complicated evacuations.

This study found that the risk for complicated evacuation is not uniform across the City of Austin. Bulk lane demand negatively impacts block groups with high population density, especially those containing multi-family residences and large student populations. Block groups most affected by the distance to arterial roads metric are found to be in the suburban/exurban areas at the city fringe and in the central urban core between the two north-south arterials. High rates of intersection occurrence has detrimental effects on block groups in the urban core, where the road network is characterized by dense, tightly configured city blocks, and in suburban areas with high numbers of cul-de-sacs. Vulnerable facilities are found to affect block groups across the study area, with no apparent pattern, and to varying degrees.

Inequitable risk for complicated evacuations is found for vulnerable populations in Austin. Specifically, minority populations and households with low income are more likely to experience slower egress during an evacuation due to high bulk lane demand. Low-earning households are also more likely to experience higher rates of intersection occurrence while evacuating, though they are more likely to reside near arterial roads.

CHAPTER I

INTRODUCTION

Transportation networks in urban areas are often complex and are becoming increasingly congested (Schrank & Lomax 2009). In many cities they carry many more people than they were built to serve, and as urban populations increase, the strain on these roadways only worsens. In crisis situations, congestion can hamper emergency management efforts, particularly evacuation. When areas are threatened by disaster, efficient evacuation can be the difference between life and death.

Growing populations also increase hazards, the potential for loss, in this case human life, and risk, the probability that this potential will be realized. Dense urban development means more people are in harm's way when disaster strikes. Railroads that were once on the outskirts of cities are now enveloped by urban sprawl. After the World Trade Center attacks in 2001, there is a greater concern that high-density urban areas are seen as targets for terrorist attacks (FEMA 2009).

The combination of increased hazard risks and congested roadways in urban areas make planning for evacuations more important than ever. It is a complex social, temporal, and spatial endeavor with many variables, and there are many variables that make evacuation difficult. Individuals become fearful, and this anxiety affects judgment (Mukai et al. 2007). People drive more aggressively and make poor routing decisions, resulting in accidents and delays (Petruccelli 2003). Vulnerable populations, such as the elderly and imprisoned, pose logistical problems (Chakraborty et al. 2005; Wolshon et al. 2005b). These issues affect an area's evacuation capability: its ease-of-egress. Among the greatest factors affecting an area's evacuation capability is the transportation network's ability to move people to safety. Depending on the type of hazard, routes can be blocked, damaged, or destroyed (Cova and Johnson 2003). Roadways become congested, and this is exacerbated by inbound emergency vehicles (Rizvi et al. 2007). Complex road networks hinder egress at intersections and other bottlenecks (Cova and Johnson 2003; Chen et al. 2007; Joint Transportation Research Center 2007) and this congestion propagates upstream, slowing egress even more (Joint Transportation Research Center 2007; Schönhof and Helbing 2008). The capacity of roadways is critical to efficiency, and as more people use them, this limited resource becomes scarce (Church and Sexton 2002; Cova and Johnson 2003; Pal et al. 2003).

There is no one solution that can be applied to all evacuation types and scales (Chen and Zhan 2008). In coastal areas, the threat of hurricanes allows for the assumption of total, or at least zonal evacuations. While this is a daunting task, emergency response planners have the benefit of knowing the scale and scope of their efforts, resulting in a finite set of complicating circumstances. This permits the implementation of system-wide staging and contraflow protocols where lanes flowing into the evacuated area are reversed in order to move people more quickly out of harm's way (Wolshon et al. 2005a, 2005b). Cities that are relatively safe from large natural disasters more often count on either ad hoc evacuation plans that are customized on the fly and tailored for the type, area, and scale of the impending disaster (Cova and Church

1997), or so called "fantasy documents" that are designed more as tools for reassuring the public that a plan is in place than as a viable emergency response plan. This mindset is borne of prohibitive budgetary constraints, and the practically infinite iterations of possible disaster scenarios (Kendra, et al. 2008).

Technology and sociopolitical challenges have changed the nature of risk in urban areas. In 2007, an estimated 2.2 billion tons of hazardous material were transported in the United States (US Census Bureau 2007e). Aside from posing risks from accidental spills, the acquisition of these types of materials by terrorists, foreign and domestic, has become a growing concern (Field 2004; Chalk 2007). Threats of terrorism, chemical spills, fire storms, and the like will not always necessitate evacuations of entire cities. Within the context of this study, these types of hazards will be referred to as urban extreme events. These differ from larger natural hazards, such as hurricanes, regional flooding, and earthquakes, in that they affect much smaller areas and populations.

Urban extreme events will threaten relatively isolated portions of an urban space, and this spatial variability, coupled with the wide range and severity of different types of urban extreme events, make the comprehensive planning for evacuations of urban areas difficult, if not impossible. This difficulty is referred to as the indeterminable evacuation planning zone problem (Cova and Church 1997), which asks how an evacuation can be planned if the size and location of the population to be evacuated cannot be identified beforehand.

A small-area urban evacuation is one where the subject population occupies only a portion of the city. It can happen immediately before, during, or after an urban extreme event. Small-area urban evacuations are common, and examples abound. In January of

2005, a train carrying chlorine gas derailed in Graniteville, South Carolina calling for the evacuation of 5,400 people. Eight people died, and over 200 were injured (Chemical & Engineering News 2005). In July of 2006, a hydrochloric acid spill forced the evacuation of a portion of Salt Lake City, Utah (KSL.com 2006). In October of 2006, 15,000 were evacuated during a chemical plant fire in Apex, North Carolina (Raleigh News & Observer 2006). Another hydrochloric acid spill in May of 2008 forced 3,000 people in Lafayette, Louisiana to flee, including 161 nursing home residents. A total of 35 people were injured (CBS News 2008).

Frequent evacuations from the fire-prone suburban-wildland interface areas in central and southern California illustrate the need for better evacuation planning. These suburban developments are menaced by brush fires during the driest months. In 1991, slow action by officials and residents alike resulted in the death of 25 people who were trapped by flames as they were evacuating their Oakland Hills homes (Trelles and Pagni 1997).

A complicated evacuation exists in an area that, for a variety of reasons, has a significantly slower rate of egress than those in surrounding areas. These areas form the weakest links in the evacuation process. A way to help mitigate emergency evacuation is to identify those areas and populations that are at greatest risk for complicated evacuations that could hinder egress and result in greater rates of injury and death (Lu et al. 2005). Armed with this knowledge, emergency planners can prioritize their planning efforts so that the needs of more vulnerable areas are addressed effectively. Using Austin, Texas as the study area, this research explores a method to identify areas that are vulnerable to complicated evacuations through a system-wide analysis of Austin's transportation network characteristics and its ability to effectively move people out of harm's way. This method determines the evacuation capability of census block groups through the examination of four variables: bulk lane demand, intersection frequency, distance to arterials, and vulnerable facilities.

Bulk lane demand can be thought of as the number of individuals using a particular stretch of road (population/combined roadway length). The greater the bulk lane demand, the more difficult egress becomes, with the capacity of the roadway being the constraining factor. Intersection occurrence frequency (number of intersections/simple roadway length) is an indicator of network complexity. The more often a driver encounters an intersection along an evacuation route, the slower their egress will be. The distance that an evacuee must travel to access a major arterial also affects the rate of egress, as distance translates to time-cost. Vulnerable facilities are those that house populations who require special attention during an evacuation. These include hospitals, nursing homes, schools, and incarceration facilities.

By quantifying these factors and combining the results, an overall assessment of complicated evacuation risk can be made for discrete spatial units, in this case census block groups. This method could aid emergency planners in identifying areas of their city that are at greater risk for complicated evacuations, allowing for a focused analysis of these more urgent cases.

After establishing where these high-risk areas are within the study area, a statistical analysis is conducted to identify who is disproportionally affected. Working from within an environmental justice framework, this portion of the thesis takes the results of the network analysis and uses them to explore issues of social equity among the population of Austin, particularly the issues of equal access and social vulnerability relative to evacuation from disaster. Are there trends that indicate a socioeconomic bias in certain groups' abilities to evacuate during urban extreme events? The complicated evacuation analysis results are compared to areas with high percentages of minorities and elderly residents, as well as low median household income. The results from both analyses are compared to population density. This complimentary analysis can be used to guide future general urban planning efforts, as well as tailor mitigation efforts for maximum efficacy.

Because this study tests for evacuation capability based on different factors that contribute to evacuation difficulty, stating a single hypothesis is problematic. Detrimental transportation network characteristics of inner-city block groups (i.e. bulk lane demand and high intersection occurrence) could increase the vulnerability of low-income and minority groups. On the other hand, the detrimental transportation characteristics of suburban neighborhoods (i.e. distance to arterials) may compromise the ability of high-income, non-minority groups to efficiently evacuate. So, while reasonable hypotheses can be made about the vulnerability of particular socioeconomic groups to complicated evacuations during urban extreme events based on singular components of this study, the combined results are likely to reveal trends that indicate difficulty for a variety of groups.

By providing a tool for emergency planners to perform a general study of evacuation capability conditions city-wide, this method could allow for a more focused, efficient, and budget sensitive use of resources. By identifying those areas that are prone to complicated evacuations, planners can take steps to insure a more successful egress.

These steps might include lane-based evacuation protocols and traffic light timing, where directional flow at intersections is managed in a way that reduces bottleneck effects, as well as the dissemination of evacuation plan materials. This method could also be used in concert with hazard risk maps to find intersections of high hazard risk and high complicated evacuation risk, allowing for an even more focused analysis of at-risk areas.

A statistical demographic analysis of those areas at high risk can allow planners to identify concentrations of populations that are socially vulnerable, such as minorities, the poor, and the elderly, whose general social equity is further diminished by their vulnerability to complicated evacuations. This information is also useful in the customization of the types and delivery methods of educational material aimed at efficient egress.

While this study concentrates on one city, the methods could be applied to any city in the United States. The methodology could conceivably be adapted to any subdivided urban area if the subdivisions had transportation network and socio-demographic data.

This research seeks to develop a method for assessing the evacuation capability of census block groups in an urban area. It also aims to reveal the diminished evacuation capability of socially vulnerable groups. This is accessible to emergency planners with limited resources. To achieve this broader goal, this study will answer two questions:

1. Which block groups in the study area are prone to complicated evacuations that will likely result in slow egress?

2. Are certain socioeconomic groups in the study area at greater risk for hindered egress during extreme urban events?

CHAPTER II

LITERATURE REVIEW

While the discussion of evacuation is not new to geographers, planners, politicians, transportation engineers, and concerned citizens, research on urban small-area evacuation has produced a relatively small body of work when compared to large-scale evacuation studies. This focus on large-scale evacuation is the result of demand on state and federal emergency management organizations to produce comprehensive response plans for large areas prone to wide-reaching natural hazards such as hurricanes (Wolshon 2005b). While this work is certainly necessary, concerns about other types of evacuations are often underfunded and neglected. A review of urban small-area evacuation research reveals the need for an effective solution for addressing this growing need.

Regional evacuations

Framing a discussion of urban small-area evacuation research within the context of more regional evacuation research is important in that it exposes problems that hinder the translation of methodology from one scale to another. The nature of regional hazards are well known, whereas the sources of urban hazards are numerous, extremely variable, and often mobile. Regional hurricane evacuation planners, for instance, benefit from a set of reasonable assumptions and a wealth of experience. Through the monitoring and prediction of storm movement, preparation for response can often begin days in advance. Mass transportation can be staged for evacuations, and officials can coordinate communication efforts with the media. A zonal threat assessment is tailored to the approach and severity of the storm, thereby identifying those areas that are likely to require evacuation. Safe zones are established, shelters are arranged, and, when the evacuation begins, contraflow protocols and lane-management plans can be enacted; all before the hazard is upon them (Wolshon et al. 2005a, 2005b). With few exceptions (i.e. Hurricane Katrina, Hurricane Rita), modern hurricane evacuation procedures are well tested and effective at mitigating the risk of injury and death for those who choose to abide by them.

On the other hand, urban extreme events can strike with little or no warning, and with great spatial variability, making evacuation planning extremely difficult (Cova and Church 1995). Plans for these types of events are necessarily generalized, and responses are devised during the immediate aftermath. Planning for an evacuation in the wake of a terrorist attack, for instance, suffers from the difficulty of predicting an event with a virtually infinite set of possible manifestations. These are a different breed of emergency and therefore, they require a different approach.

Neighborhood-scale evacuation analysis

While the volume of research on neighborhood-scale evacuations is small, important progress has been made. Notable work in the realm of micro-scale analysis of regional networks has largely sprung from collaborations between Thomas Cova and Richard Church. They were the first to examine possible complicated evacuations at the neighborhood scale (Cova and Church 1995), and their subsequent work expanded this concept to regional analyses. They published a method for systematically identifying neighborhoods that were vulnerable to difficult evacuations (Cova and Church 1997). Using Santa Barbara, California as their study area, they employed a critical cluster model to determine bulk lane demand in an effort to minimize the aforementioned indeterminable emergency planning zone problem. They used Thiessen polygons around each node (intersection) in the network to aggregate population values, and identified the node within a selected cluster of intersections that would experience the most difficulty during an evacuation. By estimating the population served by an exit, they were able to estimate how egress difficulty increases as their exit's load was compounded. This method only establishes a node's difficulty level at the start of an evacuation. It is also limited by its use of small, isolated clusters for testing with little consideration of edge effect. The results were combined to create a study area-wide mosaic map that can be useful when combined with hazard vulnerability data.

Church and Sexton (2002) tested the efficacy of the bulk lane demand model by applying a micro-scale traffic simulation model to a neighborhood, Mission Canyon, in Santa Barbara, California, which was identified as high-risk by Cova and Church (1997). This simulation confirmed the utility of the bulk lane demand model, lending weight to the idea that a general, system-wide analysis of an urban area can be used to prioritize focused, fine-grain analyses.

Mitigation

While little has been done to identify urban areas that are at greater risk for complicated evacuations, there are many new developments in the arena of mitigating the negative effects of these types of evacuations. Cova and Johnson (2003) recognize the flow-limiting effect of intersections during an evacuation. They developed a network flow model designed to optimize the transportation network during an evacuation by changing the mechanics of intersections. By managing the directional flow at especially limiting intersections, bottlenecks are minimized, allowing for more efficient egress. A study of traffic signal timing in Washington, D.C. (Chen et al. 2007) took a similar approach to the intersection problem. It found that altering the cycle times at stoplight intersections could significantly reduce egress times in urban areas. These types of neighborhood-level actions are methods that could be employed in areas identified as being vulnerable to complicated evacuations in a system-wide analysis.

Concerned with the exit bottleneck problem in fire-prone residential developments, Cova (2005) proposes that development codes should be updated to require a certain number of exits based on the population of an area. This type of requirement is the norm in building egress codes, but has not been expanded to the neighborhood scale. This concern is based on earlier research on bulk lane demand. By applying the methods used to determine the minimum number of exits required by building codes to larger spaces, he develops recommended code changes for residential areas at the fire-prone urban-wildland interface.

The emerging field of intelligent transportation system research and its application to evacuation problems is very promising. In short, intelligent transportation system technologies can optimize egress by dynamically routing traffic based on network conditions across a system. This requires that vehicles on the network contain devices that interact with a monitoring system and/or each other. This monitoring system is constantly assessing congestion conditions system-wide, and it sends routing information back to individual vehicles as a way to minimize delays. Rizvi et al. (2007), concerned with delays and accidents associated with inbound emergency response vehicles' interactions with outbound evacuation traffic, propose an intelligent transportation system solution that monitors system traffic during an evacuation and predicts if, when, and where emergency vehicles will meet outbound traffic. Using this prediction, warning notifications can be sent to all parties allowing time for mitigation.

Dresner and Stone (2004), in a general study of urban traffic, take the intelligent transportation system concept a step further and suggest the possibility of autonomous vehicle navigation as a means to manage congestion at intersections. This was proposed as a method to improve day-to-day traffic conditions, but its value in evacuation scenarios is implicit. By removing human choice, which is compromised by fear during emergency situations, egress becomes more efficient. While the theories behind such intelligent transportation system applications could be viable down the road, privacy concerns and the cost and difficulty of implementing such a system makes it unlikely to be realized in the near future. Until then, other avenues for identifying and mitigating complicated evacuations must be explored.

Ultimately, the methods for mitigating complicated evacuations depend on the conditions in the area to be evacuated. Customizing an effective evacuation plan requires knowledge of the types of hazards and the complicating factors that threaten a specific area.

Environmental justice

Ideally, risk is distributed fairly across space, where no group is burdened with inequitable danger. This concept of environmental justice has received much attention from the geographic community, but rarely is it discussed in terms of evacuation, and even more rarely, relative to the small-scale urban evacuations with which this study is concerned. In a broad survey of literature concerning ethical considerations during emergency response and recovery, Solimon and Rogge (2002), while pointing out inequity of service and access during many phases of emergency management, reported very little on the subject of evacuation. They did, however, discuss a general need for consideration of "vulnerable and disenfranchised populations, including children and elderly individuals; people who are physically and mentally challenged; ethnic, racial, cultural, and religious populations; and people who are poor" when planning and executing emergency management operations.

Some issues affecting large urban and regional evacuation also apply to small-area evacuations. Problems with broad-scope evacuation planning include assumptions that neglect the needs of the poor, elderly, and infirm among us. An assumption that can place poor populations at greater risk is that of vehicle ownership and access (Kendra, et al. 2008). Evacuation plans that take individual household vehicle ownership for granted overlook the possibility that low-income households are more likely to depend on public transportation for their daily mobility needs. During an urban extreme event, and the consequent evacuation effort, public transportation could be overloaded, and possibly unavailable, leaving those without transportation of their own stranded inside the evacuation zone. Assumptions of professional responsibility can place the elderly and infirm at a disadvantage during an evacuation. Insufficient planning on the part of those charged with the care of vulnerable people, such as hospital and nursing home administrators and staff, can result in injury and death. Wheelchairs and medical equipment can be bulky and dangerous to transport, necessitating special consideration when planning for transportation needs (Carpender, et al. 2006). Negligence, in this respect, can have disastrous results. During the evacuation of New Orleans before and during the Hurricane Katrina event, there were many instances where staff failed to evacuate residents and patients of nursing homes and hospitals, resulting in many deaths (Kendra, et al. 2008). During the Hurricane Rita evacuation of the Texas Coast, 23 nursing home patients died when overheated brakes ignited poorly stored medical oxygen tanks, incinerating their bus. It was reported that several nursing homes used busses with no air conditioning during the evacuation; a situation that could prove deadly for the aged considering the long egress times and severe temperatures. Nearly a dozen nursing homes had evacuation plans that used the same bus company, resulting in a transportation shortage, and many nursing homes were found to have no evacuation plan at all, in spite of state regulations requiring it (Kendra, et al. 2008, Zachria and Patel 2006).

If socioeconomically vulnerable populations are at greater risk for complicated evacuations during extreme urban events, how do situations like this arise? The disproportionate siting problem, central to the environmental justice debate, asks if inequity results from a purposeful exploitation of social and economic disadvantages, where a population is placed in greater danger because they do not have the resources to defend their community from detrimental development. The converse point of view supposes that environmentally dangerous areas are more attractive to vulnerable populations because property values and costs of living are lower (Pastor, et al. 2001). If we extend these ideas into an examination of evacuation fitness, both ideas have merit. For instance, certain conditions that complicate evacuation, namely bulk lane demand via population density, are more likely to occur in areas that attract lower-income families; a situation converse to the disproportionate siting argument. On the other hand, vulnerable populations might not have the voice of strong representation in matters of infrastructure improvement, depriving these communities of opportunities to reduce the risk of complicated evacuation through the construction of better, more capable roadways.

Summary

The literature on urban evacuation contains few examinations of system-wide vulnerability for complicated evacuations at the block group level. A practical and cost effective solution that takes into account the major factors that hinder egress has yet to be reported. Municipal emergency planners and the evacuated public stand to benefit from such a solution, as it would allow for mitigation efforts to be focused on the areas that need it most.

CHAPTER III

METHODS

Study area and data

The subject of this study is Austin, Texas (Figure 1). The Austin area has experienced an explosive population boom over the last few decades. Between 1980 and 2000, the population of the Austin metropolitan statistical area increased from 585,000 to 1,249,736 people, a 114% increase (City of Austin, 2005). The establishment of large-scale producers of technological products initiated an influx of "high-tech" workers from across the country and the globe. Additionally, the University of Texas at Austin has grown to become one of the largest universities in the United States, with 50,995 students enrolled for the Fall 2009 semester (University of Texas 2009). The rapid increase in population has not been countered with an effective management effort to mitigate the inevitable traffic problems associated with such growth. Among other factors compounding these local causes are commuter traffic between Austin and outlying communities, and heavy freight traffic to and from Mexico, both of which add a substantial load to Austin's already strained road network.

This study employs transportation network, demographic, and census block group delineation data. It also employs location data on vulnerable facilities that house people who require special attention during an evacuation, as well as information on the capacity

Figure 1: Study Area- Austin, Texas

of these facilities. The transportation network data for the study area and adjoining spaces were acquired from the Capital Area Council of Governments (CAPCOG) for Travis and Williamson counties. This dataset includes attribution from the U.S. Census

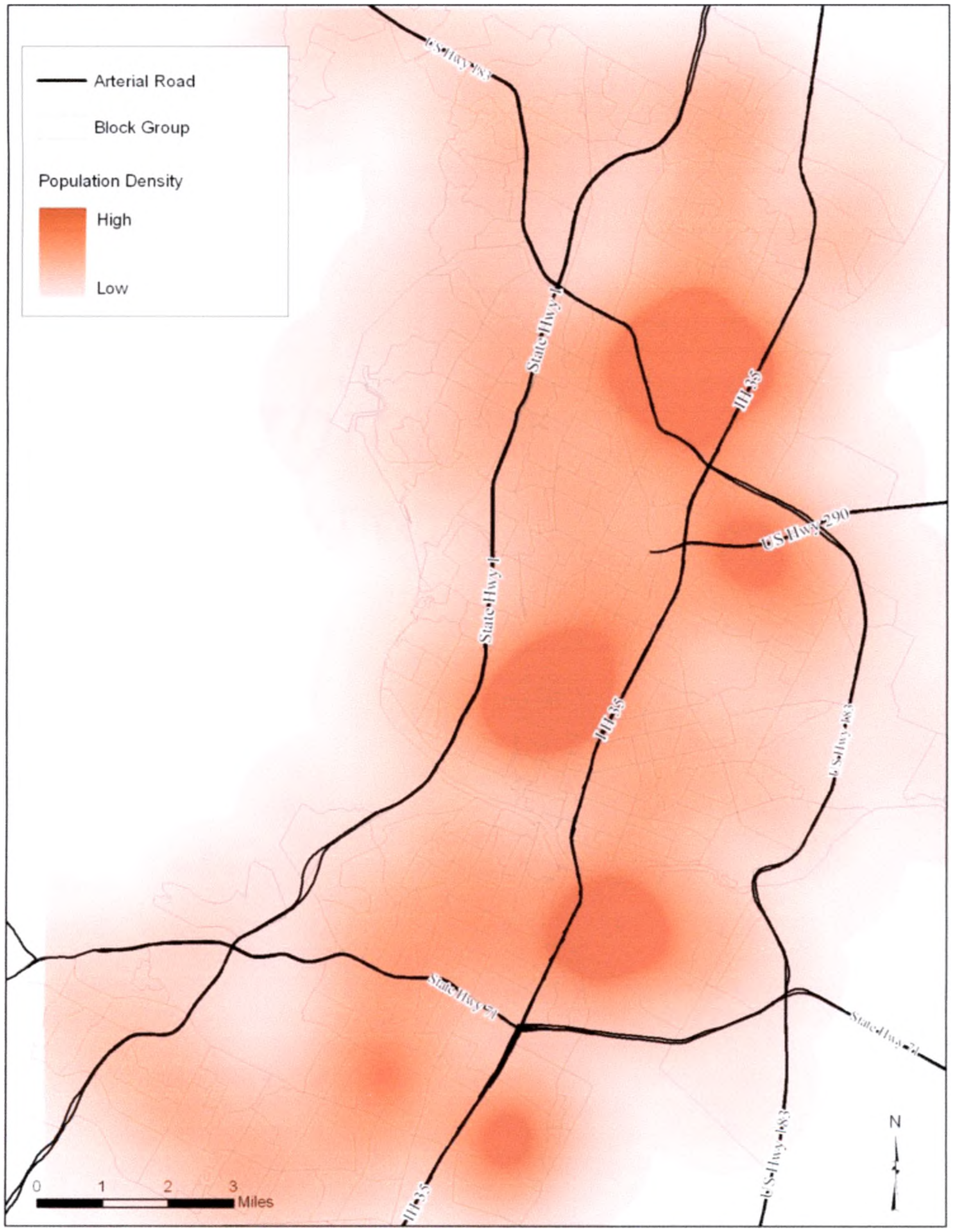

Figure 2: Population Density

Bureau Feature Class Code designations, allowing for the estimation of the number of lanes on a particular class of road, and for the identification of major arterial routes (i.e. state and federal highways). From these data, derivations for intersections, linear distances, arterial access points, and closest facilities are calculated.

The demographic and study unit delineation data are 2000 census block group data from the U.S. Census Bureau. The study area is subdivided into discrete units (block groups) with corresponding census data about those who live within a given unit. Useful attributes include population density (Figure 2), income, age, and race. Austin city limits were acquired from CAPCOG. Data on vulnerable facilities were compiled from various public data sets, phone inquiries on capacity, and by geocoding known facility addresses.

Methodology

Assessment of complicated evacuations

To answer the question of where complicated evacuation is likely to happen, four indicators were examined for each census block group: bulk lane demand, intersection occurrence frequency, distance to arterials, and vulnerable facility capacity. The effect of each of these risk factors was quantified for each block group and this value established the block group's rank among all other units.

Bulk lane demand is a comparison of the total outbound road length of the transportation infrastructure of an area and the number of people which it serves. Higher bulk lane demand makes it more difficult to move people out of an area. It leads to congestive, compressed flow along a roadway because more people are competing for a limited transportation network resource. This value was determined by first calculating the total length of all road lanes in one direction based on the likely number of lanes for all road segments within a block group. The source data for this analysis is an Austin streets shapefile from the Capitol Area Council of Governments, which includes the Census Feature Class Code (FCC) for each roadway. The street layer was clipped to each census block group boundary. FCCs for the road network layer were used to assign the likely number of lanes for road segments. The lengths of two-lane roads are counted once, the lengths of four-lane roads are counted twice, and so on. Total road length for each census block group was calculated. Arterials that traverse a block group were not included in this analysis, as vehicles are considered to have exited the area once they access an arterial. The population for each block group was divided by its total outbound lane length to provide its bulk lane demand.

Intersection occurrence frequency is a measure of network complexity. It compares the total simple length of a block group's road network to the number of intersections occurring within it. The more often a driver encounters an intersection during an evacuation, the slower their egress will be. A large intersection occurrence frequency ratio indicates a more complex network and, therefore, a higher likelihood for hindered egress. It is defined as the number of intersections divided by the simple network road length in a block group. For this analysis, the CAPCOG street layer was used to generate a point at every intersection in the study area. The resulting point layer was clipped to each census block group boundary, and an intersection count was derived for each census block group. The number of intersections in each census block group was divided by the simple road length (the road length without consideration for the number of lanes) to produce a ratio used in scoring.

Greater distances to arterial roads require longer driving times, and result in slower egress. The distance to arterials analysis establishes the average distance from all intersections within a block group to their respective closest access point to a major arterial road. This value was determined through a closest facility analysis of the network, where each of the intersections identified in the intersection occurrence analysis is an incident, and each arterial access point is a facility. Arterial access points were derived by intersecting the CAPCOG street network and the extracted arterial road layer. A geometric network feature class was created from the CAPCOG street layer. To reduce edge effect, a sizable portion of the transportation network outside of the study area was included in this part of the analysis. This inclusion allows populations in the study area to utilize roadways outside of the study area to reach arterial access points. No restrictions were placed on the closest facility analysis, as the CAPCOG dataset does not include information on one-way streets. No cut-off values were used, allowing vehicles to travel as far as needed to reach and arterial road access point. U-turns were disallowed, and no road network hierarchy was used, allowing the driver to use any road they choose without regard to any prescribed road suitability rules. The shortest route from each intersection incident to an arterial access point facility was calculated. All route lengths for a given block group were summed and divided by the number of intersections to derive the average network distance to an arterial road access point. This value was attributed to each census block group for scoring.

Any facility that houses people with special needs overnight is considered a vulnerable facility in the context of this study. These include hospitals, retirement and nursing homes, and incarceration facilities. Other types of facilities that would normally fall into this category, such as schools, are omitted from the analysis because the block group population data reported by the U.S. Census Bureau limit the analysis to times of the day when its population is largely at home. While a majority of schools were excluded from the study, some exceptions were made in the case of those schools that have on-campus residences such as the Texas School for the Deaf and private boarding schools. Vulnerable facilities require special, coordinated attention, potentially slowing egress. This dataset was derived from several sources, including the City of Austin's publicly available "Facilities" and "Hospitals" GIS layers, and geocoded addresses of incarceration facilities, private nursing homes and schools with onsite boarding in the study area. Capacity information was gathered from facility websites or phone queries. The capacity for all vulnerable facilities in each block group was summed and divided by the respective population of each block group to derive a ratio for scoring.

The results for the bulk lane demand, intersection occurrence, distance to arterials, and vulnerable facilities analyses were normalized thusly, where the normalized score for block group *i* (BG*i*) for factor *j* is:

$$\frac{\text{raw score for BG}i\text{ factor }j - \text{min. score among all BGs for factor }j}{\text{max. score for all BGs for factor }j - \text{min. score for all BGs for factor }j}$$

These normalized scores were used to rank the block groups; establishing a relative rank-of-capability for each block group in each category. This ordinal approach to organizing the results is justified, as the goal is to establish evacuation planning priority.

Block group scores for each category were then summed and the block groups were ranked again. By adding scores for each block group, a new score is generated that reflects the relative overall risk for complicated evacuation of each block group. This ranking order can provide a means for prioritizing areas for finer-grained, case-by-case analysis. Additionally, the Spearman's Rho test was used to reveal correlations between each of the four variables, as well as correlations between each variable and the combined score.

Inequity in complicated evacuation

The second portion of the analysis looks at relationships between a block group's evacuation capability and its socioeconomic condition. The analysis compared intersection occurrence frequency, distance to arterials, vulnerable facilities, bulk lane demand, and the combined scores from the primary analysis to each of three socioeconomic categories, percentage of minority residents, percentage of elderly residents, and low income, to test the hypothesis that socially vulnerable populations are at greater risk for complicated evacuation.

Ranks for percentage of minority residents were derived for each census block group using Summary File 1 (SF1) data from the 2000 U.S. Census. The total number of non-White residents in each block group was divided by the total population, rendering a percentage that was used for ranking. The census race groups included were Black, American Indian/Eskimo/Aleut, Asian, Hawaiian/Pacific Islander, other, multi-race, and Hispanic. Errors in the census data were found in several block groups, where the combined populations for individual races were higher than the reported total population. In these instances, the percentage of minority residents scores were adjusted to 100% (1.0). No normalization method was applied here, as the scores were percentages that already fell into the [0,1] range used in the primary analysis methodology. Block groups with a large percentage of minority residents were ranked high.

Similarly, ranks for percentage of elderly residents were calculated using SF1 data

(2000). The total number of residents 65 years of age and older in each block group was divided by the total population. Again, no normalization method was applied here, as the scores were percentages that already fell into the [0,1] range used in the primary analysis methodology. Block groups with higher percentages of elderly residents were ranked higher. SF1 data (2000) were also used to assign median household income values to each census block group. Since the study requires that low-income block groups be ranked higher, a different normalization method was used here, where the normalized score for block group *i* (BG*i*) for income is:

$$\frac{\text{max. income for all BGs} - \text{income for BG}i}{\text{max. income for all BGs} - \text{min. income for all BGs}}$$

Block groups were then ranked based on these normalized scores.

This analysis used the Spearman's Rho correlation test in an attempt to establish a statistical relationship between areas that are at greatest risk for complicated evacuations and socially vulnerable populations. Here it tests the evacuation capability of the block groups against socioeconomic data, namely percentage of elderly residents, percentage of minority residents, and median household income.

$$y = f\ (\%\ \text{elderly},\ \%\ \text{minority},\ \text{median HH income})$$

Complicated evacuation and socioeconomic variables are also compared to population density. The purpose is two-fold: first to reveal any associations between complicated evacuations, socioeconomic variables, and population density, and second, as a means to gauge compounded effects in areas prone to complicated evacuations.

CHAPTER IV

RESULTS

The following results of the complicated evacuation analysis focus on the worst performing 20% of the block groups in the study area. All correlation coefficients are Spearman's rank correlation coefficient. In addition to statistical results, qualitative observations about common characteristics of the worst performing block groups are noted.

Patterns of complicated evacuation

Bulk lane demand

Results of the analysis identifying those block groups with the highest bulk lane demand, a measure of a road network's capacity to transport the population that it serves, are as follows. Without exception, each of the worst performing block groups contain one or more multi-family residences (apartment complexes, and some student dormitories). Most of these block groups are densely populated, and those that are not had large, undeveloped spaces abutting populated areas, where the population density calculation (area/population) is skewed. Areas with large student populations are highly impacted (Figure 3).

The demographic profile (2000) of the top 20% (79) worst performing block groups is as follows. Non-Hispanic Whites comprise 38.65% of the population followed by Hispanic (29.05%), other (16.37%), Black (7.9%), Asian (4.80%), multi-race (2.65%), and American Eskimo (0.5%). The median age is 26.59, with 30.23% of the population

Table 1: Complicated Evacuation Correlations

		Bulk Lane Demand	Distance to Arterials	Intersection Occurrence	Vulnerable Facilities	Combined Factors	Population Density
Bulk Lane Demand	CC	1.000	.117	-.009	-.063	.235**	837**
	Sig (2-tailed)		.020	.861	210	000	000
	N	395	395	395	395	395	395
Distance to Arterials	CC	117*	1.000	- 026	007	.744**	.063
	Sig (2-tailed)	020		.613	888	000	214
	N	395	395	395	395	395	395
Intersection Occurrence	CC	-.009	- 026	1.000	-.032	520**	240**
	Sig (2-tailed)	.861	.613		521	000	000
	N	395	395	395	395	395	395
Vulnerable Facilities	CC	-.063	.007	- 032	1 000	182**	- 092
	Sig (2-tailed)	210	.888	.521		.000	067
	N	395	395	395	395	395	395
Combined Factors	CC	235**	744**	520**	182**	1 000	.296**
	Sig (2-tailed)	000	.000	000	.000		000
	N	395	395	395	395	395	395
Population Density	CC	.837**	063	.240**	- 092	296**	1 000
	Sig (2-tailed)	.000	.214	.000	067	.000	
	N	395	395	395	395	395	395

** Correlation is significant at the 0 01 level (2-tailed)

being of traditional college age (18 to 21-12.24%, 22 to 29- 17.99%). The average household size is 2.34 persons.

Bulk lane demand scores are not correlated with distance to arterials, intersection occurrence, or vulnerable facility scores (.117, -.009 and -.064 respectively). It is positively correlated to the combined metric score (.235). There is a strong correlation between bulk lane demand performance and population density (.837) (Table 1).

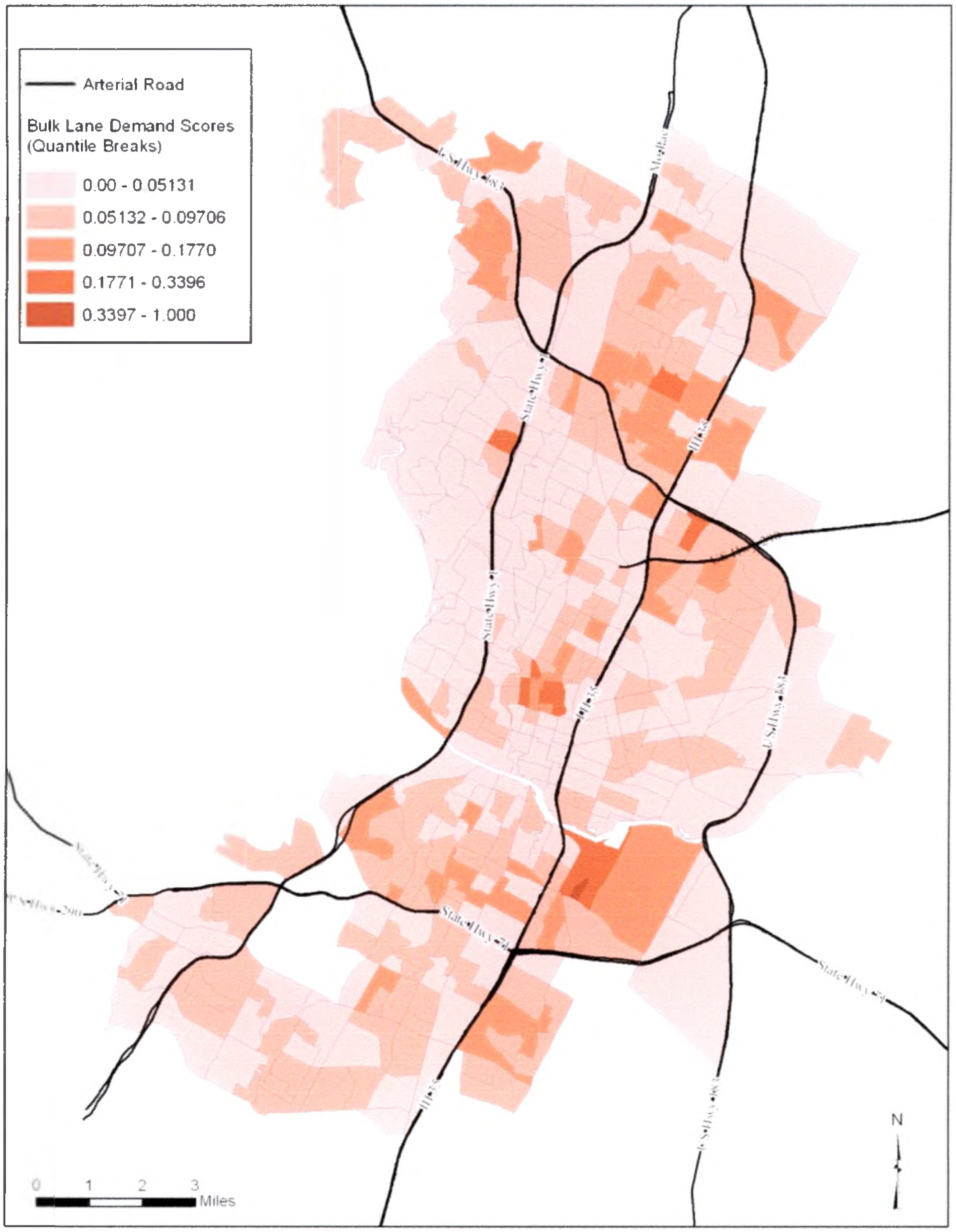

Figure 3: Bulk Land Demand Results

Distance to arterial roads

Results of the analysis identifying those block groups with the farthest distances to arterial roads are as follows. Generally, those areas most affected fall into three groups; suburban/exurban areas at the city fringe, city core block groups that lie between

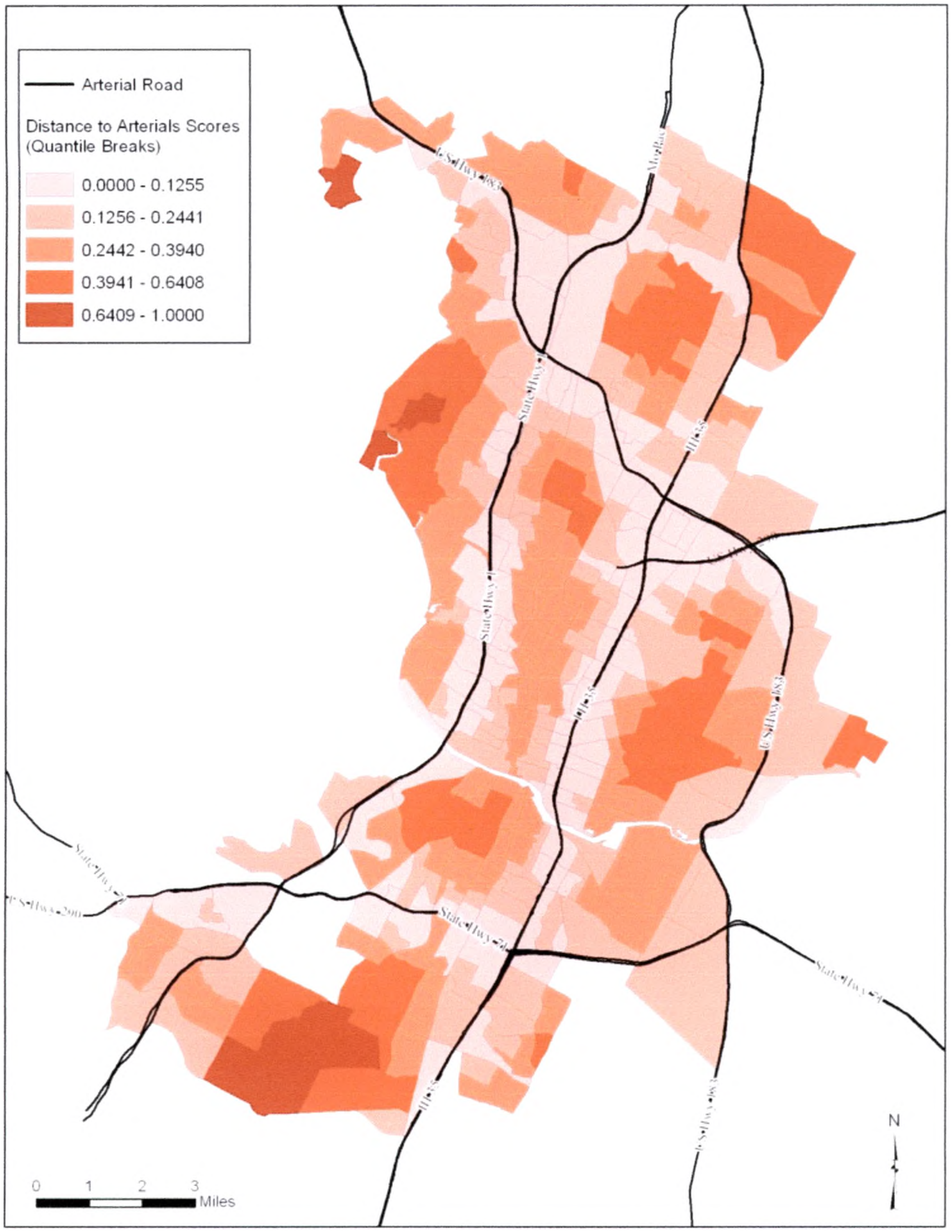

Figure 4: Distance to Arterial Roads Results

two arterials, and block groups that abut arterials but are thinly populated and, therefore, are large enough to place residents a great distance from adjacent arterial routes (Figure 4).

The demographic profile (2000) of the top 20% (79) worst performing block groups is as follows. Non-Hispanic Whites comprise 35.20% of the population followed by Hispanic (30.44%), other (15.99%), Black (11.43%), Asian (3.29%), multi-race (2.99%), and American Eskimo (0.6%). The median age is 33.99, with a demographic makeup that suggests a high number of young families (children 0-17 years old (24.87%), 30-39 years old (18.29%)). The average household size is 2.60 persons.

Distance to arterial roads performance is not significantly correlated with bulk lane demand, population density, intersection occurrence frequency or vulnerable facility scores (.117, .063, -.026 and .007 respectively). It is positively correlated to the combined metric score (.744) (Table 1).

Intersection occurrence frequency

Results of the analysis identifying those block groups with the largest number of intersections relative to total simple roadway length are as follows. For the most part, block groups in this category are concentrated in the urban core, particularly in the University of Texas campus area, the South Congress commercial district, and areas to the east of IH-35. These are dense areas with small, tightly configured city blocks. Exceptions include new suburban development areas (Anderson Mill) in the northwestern extreme of the study area, and the Franklin Park area in the southeast (Figure 5).

The demographic profile (2000) of the top 20% (79) worst performing block groups is as follows. Non-Hispanic Whites comprise 36.57% of the population followed by Hispanic (28.52%), other (14.95%), Black (10.22%), Asian (6.00%), multi-race (3.00%), and American Eskimo (0.66%). The median age is 31.08, and the largest age group block is 22-39 years of age (38.75%). The average household size is 2.16 persons.

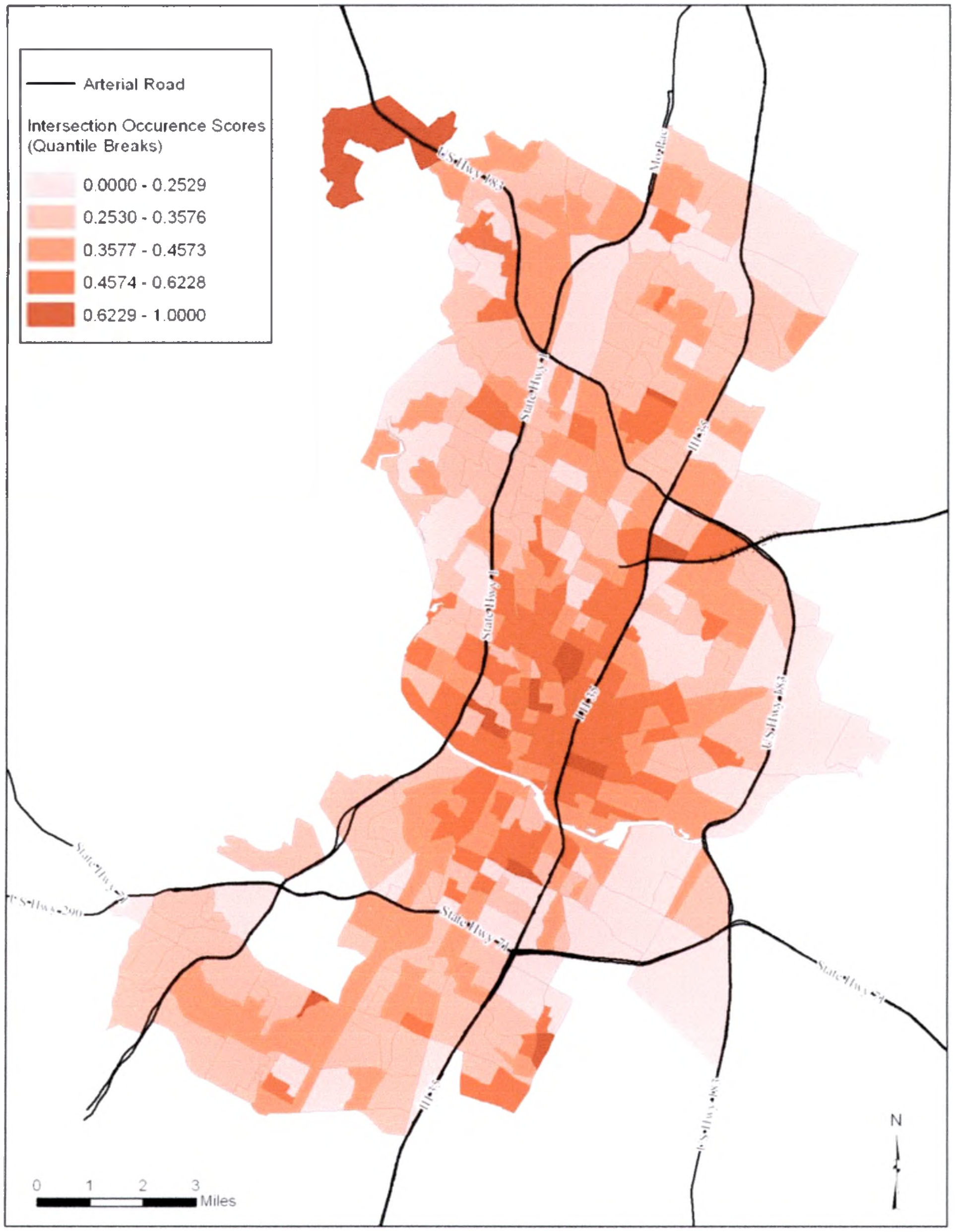

Figure 5: Intersection Occurrence Frequency Results

Intersection occurrence frequency performance is not significantly correlated with bulk lane demand, distance to arterials, or vulnerable facility scores (-.009, -.026 and -.032 respectively). It is significantly correlated with population density (.240) as well as the combined metric score (.520) (Table 1).

Vulnerable facilities

Results of the analysis identifying those block groups with the greatest number of residents living in vulnerable facilities, respective of the block group population, are as follows. As this category includes a wide range of vulnerable facility types, namely prisons, hospitals, nursing homes, and boarding schools, the types of areas that are most affected also vary widely. These facilities are located in the urban core, as is the case with some hospitals, city and county jails, and boarding schools, on the outskirts of the city in the case of the Travis State Jail to the east, and in various residential areas where nursing homes and smaller hospital facilities are located. Therefore, generalizations about common characteristics of the most affected block groups are difficult to make (Figure 6).

The demographic profile (2000) of the top 20% (79) worst performing block groups is as follows. Non-Hispanic Whites comprise 50.76% of the population, followed by Blacks (17.22%), Hispanics (14.93%), other (6.59%), Asians (6.49%), and multi-race (3.82%). The median age is 36.45, and the average household size is 1.64.

Vulnerable facility performance is not significantly correlated to population density, distance to arterials, intersection occurrence, or bulk lane demand (-.092, .007, -.032, and -.063, respectively). It is positively correlated to the combined factor performance (.182) (Table 1).

Combined measurement for complicated evacuation

Results of the analysis identifying those block groups that performed poorly overall, as expressed in their combined evacuation capability scores, are as follows. As this score considers a block group's performance in relation to four different variables, generalizations about those block groups that performed poorly are, as expected, difficult to make. Block groups in this category represent a broad variety of locations, neighborhood types, and road network configurations (Figure 7).

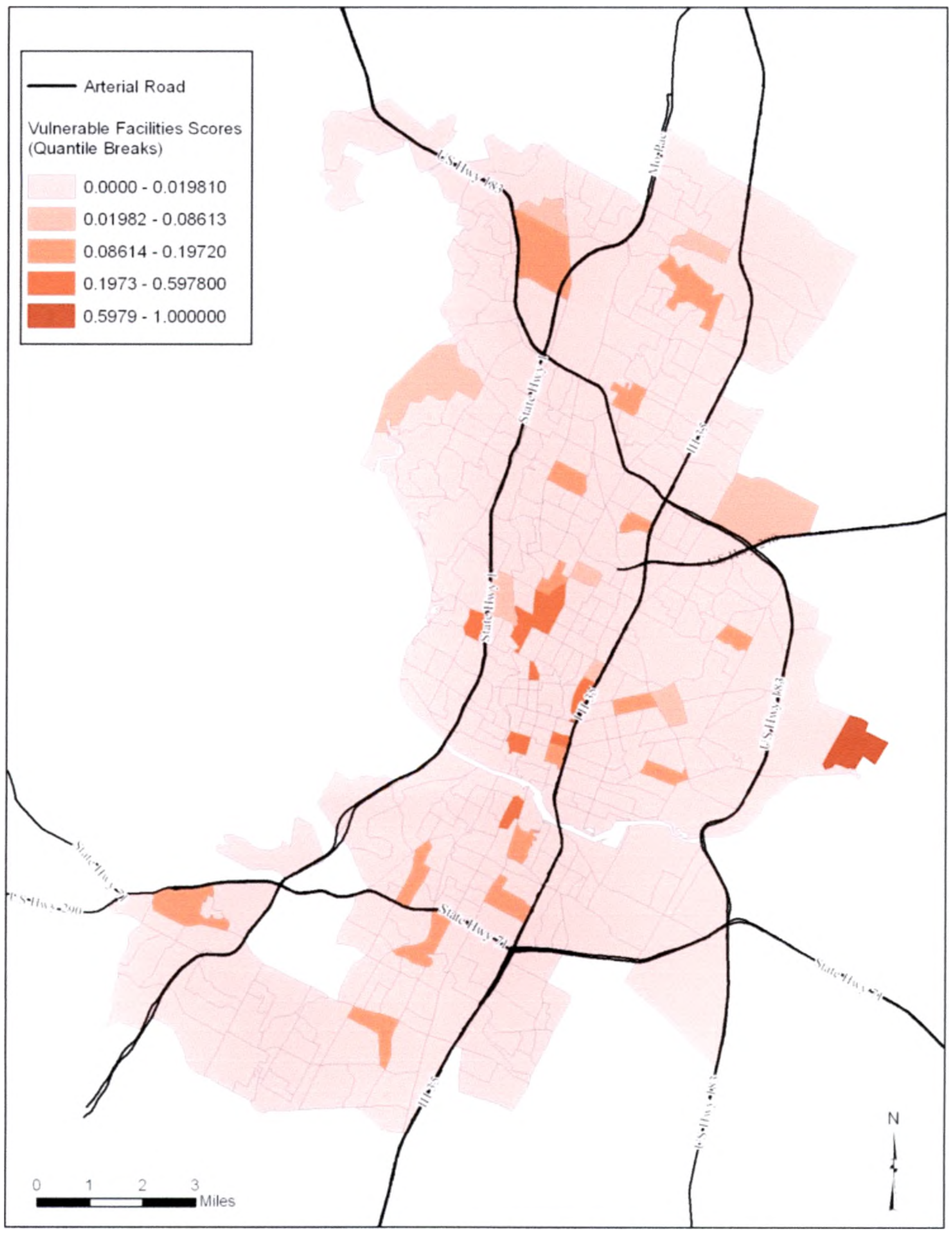

Figure 6: Vulnerable Facilities Results

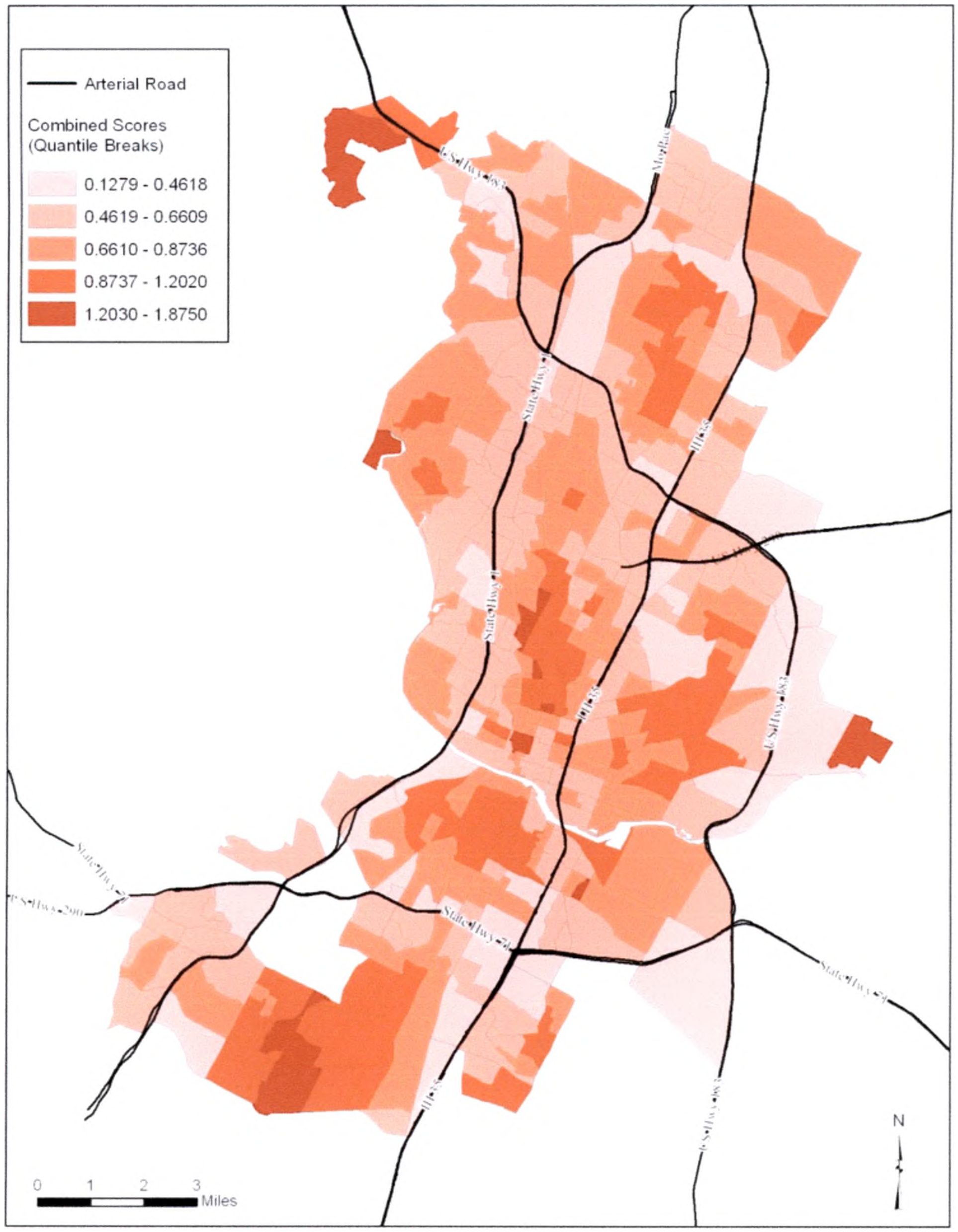

Figure 7: Combined Factors Results

The demographic profile (2000) of the top 20% (79) worst performing block groups is as follows. Non-Hispanic Whites comprise 35.10% of the population followed by Hispanic (30.05%), other (15.93%), Black (9.50%), Asian (5.36%), multi-race (3.37%), and American Eskimo (0.60%). The median age is 31.40. The average household size is 2.35 persons.

Being a composite value of the four variables to which it is being compared, the combined complicated evacuation score is naturally significantly correlated with intersection occurrence, bulk lane demand, vulnerable facility, and distance-to-arterial scores. The correlations between the four variables and the combined scores are not equal. The strongest correlation is with distance to arterials (.744), followed by intersection occurrence (.520), bulk lane demand (.235), and vulnerable facilities (.182). It is also positively correlated to population density (.296) (Table 1).

Socioeconomic analysis on inequity of complicated evacuation

The socioeconomic analysis revealed relationships between the socioeconomic variables and the complicated evacuation metric variables. There is a positive correlation between the percentage of minorities and the percentage of low income households (.575). Percentage of elderly residents is negatively correlated to both the percentage of minorities (-.233), and the percentage of low income households (-.237) (Table 2).

Block groups with the largest minority populations are concentrated to the east of IH-35, north of US-183, and south of Ladybird Johnson Lake (Figure 8). There were no significant correlations between the percentage of minority residents and intersection occurrence frequency, distance to arterial roads, vulnerable facility, or combined factor scores (-.510, -.003, -.033, and .024, respectively). However, the percentage of minority populations is significantly correlated with the bulk lane demand measurement (.327), and the population density measurement (.283) (Table 3).

Table 2: Socioeconomic Correlations

		Percent Minority	Low Income	Percent Elderly
Percent Minority	CC	1 000	.575**	- 233**
	Sig (2-tailed)		.000	000
	N	395	395	395
Low Income	CC	575**	1 000	- 237**
	Sig (2-tailed)	000		000
	N	395	395	395
Percent Elderly	CC	- 233**	-.237**	1.000
	Sig. (2-tailed)	000	.000	
	N	395	395	395

** Correlation is significant at the 0 01 level (2-tailed).

Table 3: Socioeconomic/Complicated Evacuation Correlations

		Bulk Lane Demand	Distance to Arterials	Intersection Occurrence	Vulnerable Facilities	Combined Factors	Population Density
Percent Minority	CC	.327**	- 003	- 051	- 033	.024	283**
	Sig (2-tailed)	.000	955	.311	.511	.634	000
	N	395	395	395	395	395	395
Low Income	CC	357**	-.108*	171**	052	090	411**
	Sig (2-tailed)	.000	032	001	.301	074	000
	N	395	395	395	395	395	395
Percent Elderly	CC	- 368**	049	.030	065	- 037	- 242**
	Sig (2-tailed)	.000	.333	558	195	.460	000
	N	395	395	395	395	395	395

**. Correlation is significant at the 0.01 level (2-tailed).

Block groups with the lowest median income are concentrated east of IIH-35, and in areas where there are large numbers of students (Figure 9). Low income scores were not significantly correlated to vulnerable facility or combined factor scores (0.088 and 0.091, respectively) There are positive correlations to intersection occurrence frequency (0.221), and bulk lane demand (0.269) scores, as well as to population density (0.327). Income scores were negatively correlated to distance to arterial scores (-0.177) (Table 3).

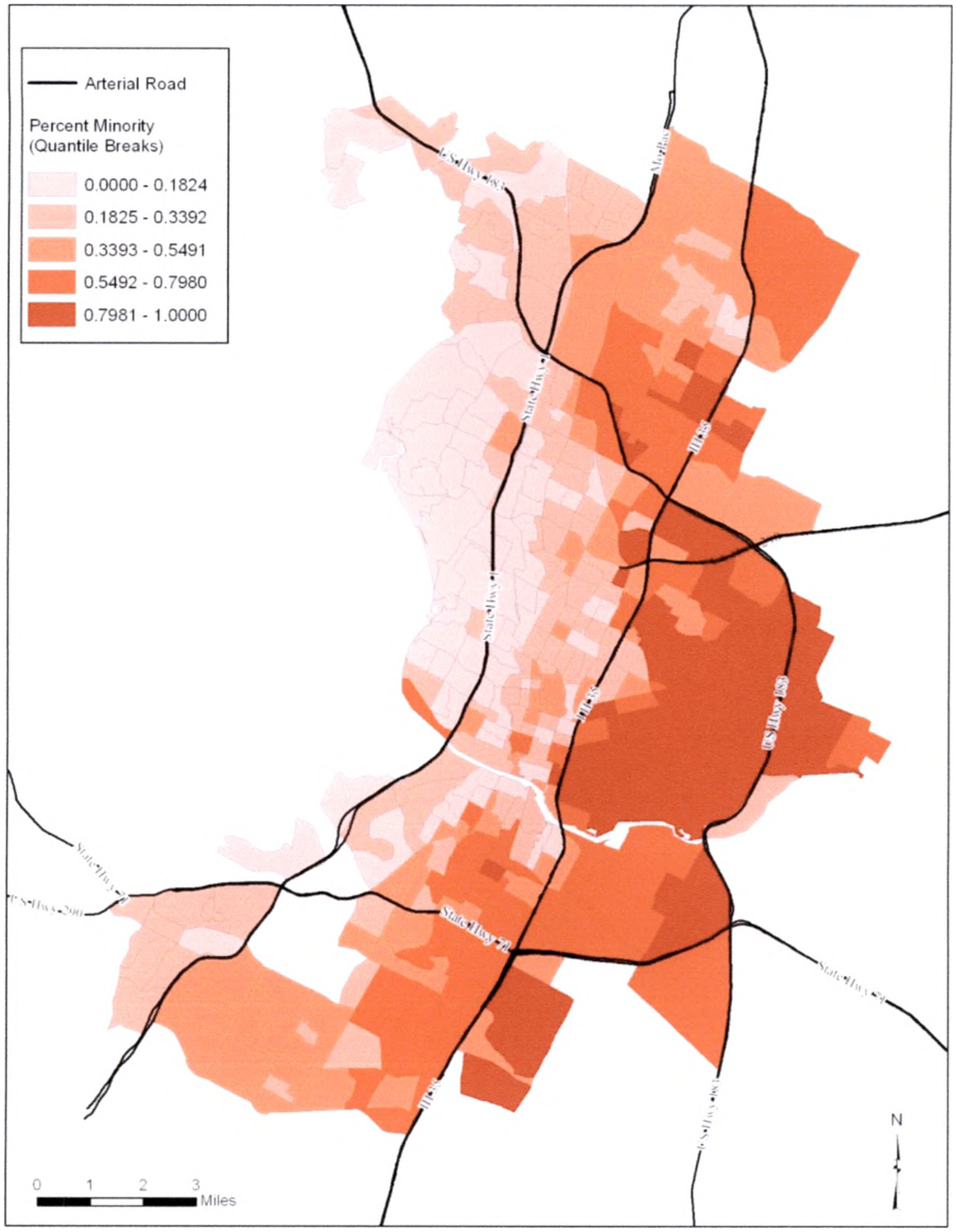

Figure 8: Percentage of Minority Residents

Block groups with the largest percentage of elderly residents are largely concentrated west, and immediately east, of SH-1, and in pockets east of IH-35 (Figure 10). Percentage of elderly residents scores are not significantly correlated to intersection occurrence frequency, vulnerable facility, distance-to-arterial, or combined factor scores for complicated evacuation (.030, .065, .049, and -.037, respectively). They are negatively correlated to bulk lane demand scores (-0.368) and population density (-0.242) (Table 3).

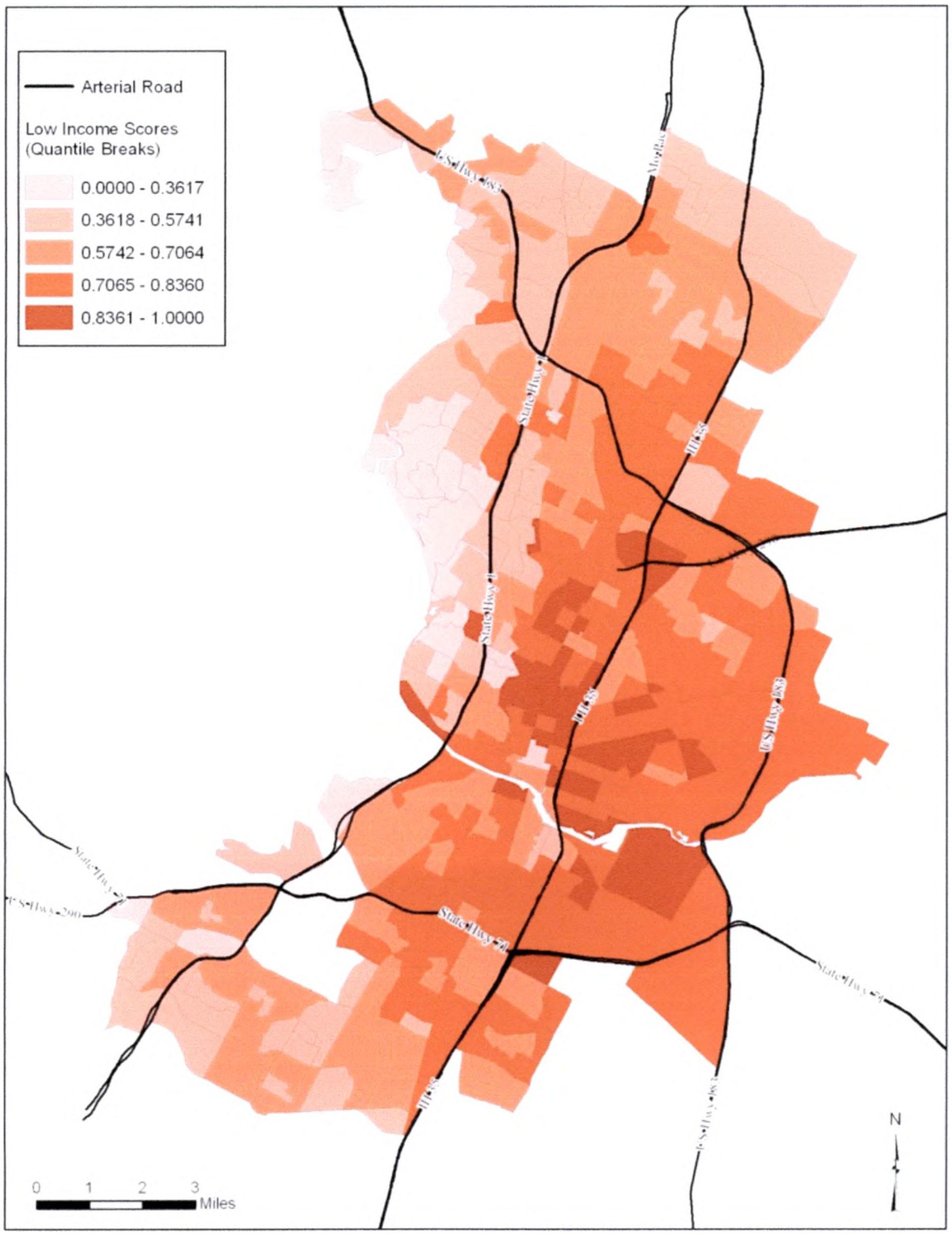

Figure 9: Median Household Income

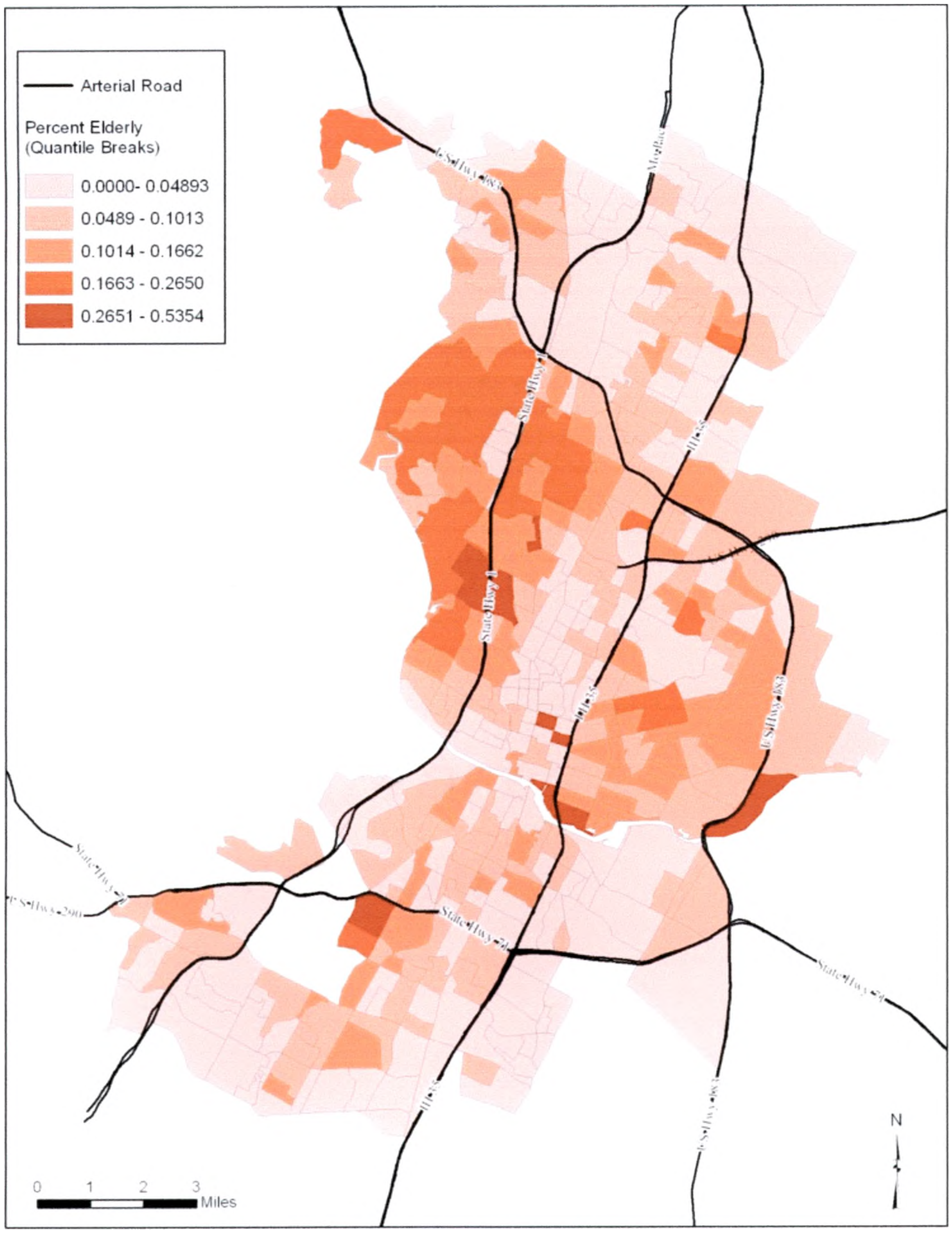

Figure 10: Percentage of Elderly Residents

CHAPTER V

DISCUSSION

The first part of this study sought to develop a method for identifying areas in Austin, Texas that may be prone to complicated evacuations based on a combination of four variables: bulk lane demand, distance to arterial roads, intersection occurrence frequency, and vulnerable facilities. The analysis identified block groups that could be at greater risk of slow egress during an evacuation. It also revealed which of these variables play the greatest roles in affecting an area's evacuation fitness. The second part of this study attempted to establish whether or not certain socioeconomic groups are at greater risk for complicated evacuation. While there were no significant correlations between the combined complicated evacuation scores and scores for percentage of minority residents, the percentage of elderly residents, and the low income scores, interesting relationships between these scores and the evacuation variable scores were revealed.

Bulk Lane Demand

Bulk lane demand is significantly related to percentage of minority residents, percent elderly, low income, and population density. The relationship between bulk lane demand and population density makes perfect sense; as more people populate a space, resources, in this case the transportation network, become scarcer. Unless more roads are built, more people add stress to the network, reducing the efficacy of the system. The fact that those block groups that performed poorly in the bulk lane demand analysis contain large, multi-unit dwellings, such as apartment complexes and student housing is of no surprise. The units making up these complexes are generally smaller than single family houses, and are more tightly situated than typical neighborhoods where yards and driveways reduce density. Additionally, these complexes are multi-level, ranging from a few stories to towering high-rise condominiums and student dormitories such as the University of Texas' 3,200 resident, 14-story Jester Hall, greatly compounding density. The moderate average household size of 2.34 in the block groups that performed poorly (as opposed to the city-wide average of 2.36), is trumped by the sheer number of households in a given space.

Distance to arterial roads

Results of the distance to arterial roads analysis show that there are three types of block groups in the study area. First are those block groups in the urban core that fall between IH-35 and SH-1. Residents of these block groups must travel away from the urban core to reach one of these arterials, and their central location could prove to be problematic during an evacuation. The second type of affected areas are block groups that lie away from the urban core in more suburban and exurban areas that are spatially isolated from arterial thoroughfares. A less common affected type is block groups that actually abut a major arterial (IH-35). These block groups are thinly populated and, therefore, are quite large relative to most other block groups in the study area. These block groups perform poorly in the distance to arterials analysis because their neighborhoods are situated in portions of the block groups that are farthest away from the highway. These neighborhoods contain the most complex road networks and, therefore, more intersections. Because the distance to arterial metric is an average distance of all intersections in a block group to main arterial access points, this type of block group is detrimentally affected.

Intersection occurrence frequency

With a few exceptions, the block groups that performed poorly in the intersection occurrence frequency analysis are concentrated in the urban core of the study area. The road network in the urban core is characterized by small, tightly situated city blocks arranged as a grid. The relatively short blocks mean that a trip down a given street will result in more intersection stops than in other areas of the city where the transportation system is less compressed.

Exceptions, those poorly performing block groups that lie outside of the city core, are characterized as being newly developed subdivisions where the road network is comprised of a few main thoroughfares that have multiple cul-de-sac spurs. Each of these spurs is short, and does not add much road length to the calculation, but does add an intersection. This results in a higher ratio of intersections to road length.

The significant relationship between intersection occurrence frequency scores and population density is primarily associated with the urban core; specifically with areas that house large numbers of students. As mentioned before, these areas are characterized both by dense, vertical, multi-unit buildings and a tightly arranged transportation network.

Vulnerable Facilities

Because this category is defined by such a variety of vulnerable facility types that are not directly related to a particular set of road network characteristics or spatial situation, no pattern is revealed through this analysis. There are no evident relationships between vulnerable facility scores and any of the other complicated evacuation variables, and because most block groups contain no vulnerable facilities as defined by this study, these scores are only slightly correlated to the combined complicated evacuation scores (.182).

Minorities

The correlation between areas with high percentages of minorities and high bulk lane demand scores can be partially explained through a closer examination of the socioeconomic data. High bulk lane demand is positively correlated with population density. Three factors play a role in linking minority groups with high population density. These are household size, housing type, and urban centralization. Minority groups have larger average household sizes, lower homeownership rates, and are more likely to live in multi-unit dwellings. Minority groups also tend to have higher absolute centralization index scores than Whites; a metric indicating the tendency of certain groups to reside near city centers. All of these factors contribute to higher population densities.

U.S. Census data shows that minority groups have higher average household sizes compared to Whites. In 2007, the average White-only household contained 2.53 members, compared to 2.76 members in non-White homes. Black-only households had

2.60 members, Asian-only households had 2.91 members, and homes of other-only races had an average of 2.78 members (US Census Bureau 2007c). Minority groups also have lower homeownership rates, meaning they are more likely to rent, and they are more likely to live in multi-unit dwellings. 2007 homeownership rates for non-Hispanic Whites was 75.2%, compared to 49.7% for Hispanic/Latino-only households, 47.2% for Black-only households, and 59.2% for all other races. This means that 50.3% of Hispanic/Latino households, 52.8% of Black households, and 40.8% of households of other non-White races are renting (US Census Bureau 2007a). Of those renting, 68.59% of non-Hispanic Black households, and 68.67% of Hispanic/Latino households rent in multi-unit dwellings (i.e. apartments) (US Census Bureau 2007a). Additionally, certain minority groups have high absolute centralization index scores. The absolute centralization index, a segregation metric developed by Massey and Denton (1988), indicates the likelihood for group members to reside close to the center of metropolitan areas. Higher scores (with 1 being the highest possible) indicate that members of minority groups reside disproportionately in central city neighborhoods The 2000 absolute centralization index scores, as derived by the U.S. Census Bureau in 2002, indicates scores of 0.722 and 0.689 for Black and Hispanic groups, respectively (Iceland et al. 2002). This tendency to live in more densely populated urban areas could help explain the correlation between high minority percentages and bulk lane demand.

Low Income

Similarly, the correlation between low income and high bulk lane demand can be partially explained by housing situations among low income groups. As would be expected, there is a very strong relationship between income and homeownership rates. Lower income households are more likely to rent, and there is a correlation between lower income and multi-unit occupation among renters (US Census Bureau 2005a).

It should also be mentioned that there is a strong relationship between race and income. 2007 estimates of median household income show that non-Hispanic White households earn an average of $54,920 annually, while Black-only households earn $33,916 and Hispanic-only households earn $38,679 on average. White-only household income is surpassed only by Asian-only household income ($66,103) (US Census Bureau 2007d).

This is also powerfully illustrated by U.S. Census poverty data. The most recent three-year poverty rate report from the U.S. Census Bureau (2003-2005) shows that the national poverty rate is 12.6% among all races. Non-Hispanic Whites have a poverty rate of 8.4%, compared with 24.7% for Blacks, 25.35% for American Indians, 10.9% for Asians, 12.2% for Hawaiians/Pacific Islanders, and 22.0% for Hispanics (US Census Bureau 2005b). The Spearman's Rho test for this study showed a moderate (.528) correlation between percentage of minority residents and income in the study area, and highlights the link between high bulk lane demand values, high percentages of minorities, and low income.

The relationship between block groups with low median incomes and high rates of intersection occurrence can, again, be partly explained by the race-absolute centralization and race-income relationships. As mentioned before, there is a tendency for those of Black and Hispanic ethnicity to reside close to the center of metropolitan areas and, per the US Census data, Black and Hispanic households tend to earn less, on average, than White households. This centralization tendency results in a higher population of low-earning Black and Hispanic households in the urban core of the city, where the tight transportation grid results in higher intersection occurrence scores.

The elderly

The analysis revealed significant inverse relationships between the percentage of elderly populations and the bulk lane demand measurement, population density, percentage of minority residents, and low income scores. This means that block groups with a high percentage of elderly residents are likely to be less dense and have lower bulk lane demand, higher income, and lower percentages of minority residents.

According to the American Housing Survey of the United States, of the sampled elderly residents that live inside metropolitan statistical areas, 63.49% live in suburban areas, as opposed to 36.51% living in central cities (US Census Bureau 2005d). This tendency to live away from the city core helps explain the higher scores in the percent elderly analysis in block groups in the central western portion of the study area. These block groups are generally characterized as suburban neighborhoods that are of a lower population density than their urban core counterparts and, therefore, have lower bulk lane demand scores.

The 2000 census data show that while median annual earnings for those 65 and older ($31,556 for men, $22,511 for women) were lower than the overall averages ($37,057 for men, $27,194 for women), they had homeownership rates of 77.6% versus 66.2% for all ages 18 and over (US Census Bureau 2004). It is likely that, while elderly residents might not earn as much as their younger neighbors, they have owned their homes for some time. This long-term tenure explains how elderly people earning less than other age groups have higher homeownership rates.

Implications for mitigation

Identifying areas and socioeconomic groups that are prone to complicated evacuations is an important step in developing a comprehensive emergency management plan, but this alone will not save lives. Armed with the knowledge of problematic areas, emergency managers can tailor mitigation techniques to an individual area's needs more effectively and efficiently. Three general approaches to mitigation should be considered.

The first addresses the issues of the road network characteristics directly. The traffic-based complicating factors in this study, bulk lane demand, intersection occurrence, and distance to arterials can be mitigated in a variety of ways, depending on where they are. Block groups in the city core and suburban areas may both perform poorly in the same category, but might require different approaches to mitigation. For instance, areas with high intersection occurrence scores could benefit from traffic signal timing during an evacuation. This method is viable in the urban core, where traffic signals are ubiquitous, but in suburban areas, where intersections are controlled by signs or traffic calming installations, this method cannot apply. Here, other mitigation techniques, such as physical, on-site traffic flow management conducted by emergency management agents (police, firefighters, and local response volunteers) should be employed. Development codes that require a minimum number of exits from an area, reducing the effects of intersection occurrence and bulk lane demand, can make new developments safer. Existing suburban neighborhoods can add exits in some cases, but this technique would probably not be feasible in existing urban areas due to the financial constraints of building new access to existing arterial roads. Here, other methods such as the aforementioned traffic signal timing and more sophisticated intelligent transportation system technologies could help alleviate problems associated with volume-driven congestion during an emergency event.

Short of building new highways, the distance to arterial roads problem cannot be mitigated directly, as it relates to an area's fixed position inside the transportation network. Since it is impossible to shorten the physical distance between a block group and existing arterial access points along existing roads, mitigation efforts should concentrate on shortening the temporal distance by working to reduce friction along critical routes through the application of the mitigation techniques discussed above.

The second mitigation approach involves developing cooperative relationships between emergency planners and organizations and entities within at-risk communities. By providing resources and guidance to neighborhood associations, schools, and vulnerable facilities, coordinated and informed evacuation plans can be developed and shared, making crises less chaotic. Does a hospital or nursing home have sufficient transportation to move its residents and critical medical equipment out of harm's way? Can a prison or jail be quickly and completely evacuated while still ensuring the safety of the general public? Are there sufficient busses and qualified staff on site to drive students and faculty away from a school to a safe location? By communicating with the appropriate parties, emergency managers can delegate responsibility while fostering awareness in affected communities.

The third aspect of mitigation is that of education. By identifying areas that are prone to complicated evacuations, assessing the needs of these areas individually, and tailoring evacuation plans to meet those needs, emergency managers are then able to educate residents of the at-risk communities to the necessary steps for a safe and successful evacuation. Additionally, by identifying at-risk communities within a city, emergency managers also have the benefit of knowing who their audience is. Educational material can be disseminated based on the residents' language, likely preferred media, and through appropriate organizations for optimum effect.

CHAPTER VI

CONCLUSION

The successful development of a methodology for identifying areas within a city that are vulnerable to complicated evacuations has the potential to save lives and reduce injuries. The method explored in this thesis study can provide a means for municipal emergency planners to prioritize their mitigation efforts through an efficient and cost-effective analysis of those areas for which they are responsible for. It can be conducted with common GIS software packages, and with relative ease. When the results are combined with hazard risk maps, emergency management planners will have a clearer picture of the tasks that lie ahead.

The statistical analysis of relationships between socioeconomic groups and evacuation capability examined differential risk for complicated evacuations in the context of social justice. By identifying at-risk populations, both spatially and socially, we can develop strategies that improve the situations that result in inequity. This statistical analysis also has a more immediate benefit: a means to develop appropriate strategies for the dissemination of evacuation planning materials to particular audiences and to address mobility needs for special groups. Are at-risk populations likely to speak languages other than English, resulting in the need for language specific planning materials? Should local evacuation strategies include enhanced access to mass transit for those that may not own personal vehicles, in the case of low-income areas, or those that may not able to drive, such as the elderly and infirm?

This study found that risk for complicated evacuation is not uniform across the study area. Bulk lane demand scores were high in block groups with high population density, especially those containing multi-family residences and large student populations. Block groups most affected by the distance to arterial roads metric were found to be in the suburban/exurban areas at the city fringe, and in the central urban core between the two north-south arterials (i.e. I-35 and MoPac). Many of the block groups with low scores in this category lie in wildfire hazard areas on the western edge of the study area (City of Austin 2003), particularly in the more populated portions of the wildland urban intermix where greater wildfire risk exists (Lu, et al. 2010). High rates of intersection occurrence had detrimental effects on block groups in the urban core, where the road network is characterized by dense, tightly configured city blocks. Vulnerable facilities were found to affect block groups across the study area, with no apparent pattern, and to varying degrees.

Inequitable risk for complicated evacuations was found among vulnerable populations in Austin. Specifically, minority populations and households with low income are more likely to experience slower egress during and evacuation due to high bulk lane demand. Low-income households are also more likely to experience higher rates of intersection occurrence while evacuating, though they are more likely to reside near arterial roads. Areas with high percentages of elderly residents were found to have lower population density, and lower bulk lane demand.

While this study was successful in answering its research questions, there are opportunities to refine the methodology for more accurate and useful results. Both the socioeconomic and transportation data have limitations, and improvement to these datasets will produce stronger results. Minor inaccuracies in the census data were found, compromising the integrity of the socioeconomic analysis. Additionally, the census data used for this study were nearly 10 years old when these analyses were conducted. Given that Austin grew rapidly, and its demographic profile has changed dramatically during the previous two decades, it is likely that the 2010 U.S. Census will reveal a continuation of this trend, and a duplication of this study using newer data would produce differences in the outcome.

The transportation dataset, while reasonably spatially accurate, lacked attribution that would have enhanced the results. Downtown Austin is made up of a complex combination of one-way and two-way streets; awkward one-way to two-way transitions; and three-, four-, and five-way intersections. By incorporating information expressing this complexity into the road network dataset, finer conclusions could be drawn about this dynamic network. In these areas, the "distance to arterials" measurement was compromised by allowing evacuees to travel by any route to the nearest arterial road for escape. In reality, these trips could be longer as a result of having to circumnavigate city blocks to reach routes that permit the desired directionality.

It is unlikely that the four factors examined in this study have equal effects on egress, though they were treated as such in the reported analyses. Quantifying these differences is difficult, but devising and applying a system to weight the component factors of this study would augment the integrity of the results. Additional future work could include analyses of multiple cities in an effort to determine if the socioeconomic disparity found in Austin is common in other large cities. Future studies could also benefit from a method to gauge the compound effects of traveling through other block groups to reach an arterial road. The current study treats block groups as isolated communities, but these populations often have to drive through other block groups while evacuating. Incorporating a means to quantify additional difficulty based on the complicating factors encountered while driving from home block groups to arterial roads would enrich the utility of the work.

Perhaps the greatest addition to this work would be the incorporation of hazard risk data. Producing a study that not only identifies areas at risk for complicated evacuations, but also shows intersections of these areas with high hazard risks would be a valuable tool for planning and mitigation. This would also enable a more refined socioeconomic analysis that could identify inequity, not only in complicated evacuation risk, but in compound risk situations where people are more likely to encounter hazards and are more likely to experience more difficulty when trying to escape danger.

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