AN EMERGENCY EVACUATION PLANNING MODEL FOR SPECIAL NEED POPULATIONS UTILIZING PUBLIC TRANSIT SYSTEMS

by

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ABSTRACT

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The need to have evacuation plans in place for readily implementation for special need populations has become evident after catastrophic events such as Hurricane Katrina. For the purpose of this research special need populations will include, but are not limited to, people with physical disabilities, senior citizens, non-English speaking populations, residents and employees without vehicles, and tourists. The main objective of this research is to evaluate different evacuation procedures for special need populations from large urban areas utilizing current public transit systems. A microscopic simulation model was constructed to analyze real life scenarios for evacuation methodologies. A linear programming optimization model was developed to find the optimum locations for evacuation bus stops for the case study area. The results from this research were very interesting and can aid evacuation planners in the future.

EMERGENCY EVACUATION PLANNING FOR SPECIAL NEED POPULATIONS UTILIZING PUBLIC TRANSIT SYSTEMS

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1 INTRODUCTION

In the past decade, large catastrophic events such as terrorist attacks and natural disasters have disrupted regional urban areas and raised awareness of mass evacuation. Advancements in technology are allocating planners to develop more efficient and effective emergency preparedness strategies to protect the general public from danger (Laben, 2002). The known destructive path of natural disasters and terrorist attacks are becoming easier to track with computer models and enhanced communication devices (Alsnih and Stopher, 2004). Growing awareness of baleful events creates a need for more advanced plans of safety. It has become evident that our society faces many dangers and being prepared for them is one means of defense.

Catastrophic events are inevitable and pose great threat to our society. Hurricanes, floods, volcanoes, and earthquakes occur worldwide leaving many urban areas susceptible to their path of destruction. Man-made dangers are becoming more prevalent with the increase of nuclear power plants and terrorist attacks. If not properly planned for these disasters have the potential to result in large amounts of destruction and causalities.

When a predicament threatens an area, sometimes the only means of safety requires fleeing. Growing populations, especially in large urban areas, require a plan to evacuate citizens in a timely and orderly fashion as to not congest and obstruct roadways. It is very difficult to predict human behavior in times of panic. Therefore, making evacuation instructions (for all possible fatal incidents) public knowledge prior to an incident can help alleviate stress and confusion during an emergency evacuation.

Emergency events that can lead to evacuation consist of natural disaster, biological threats, chemical threats, and terrorist threats. Depending on size and demographics of the evacuation area and the type of event the evacuation procedures can vary. Through the use of reproducing traffic network behavior, simulation models provide realistic results that aid in effective evacuation planning (Di Gangi et al., 2009; Mastrogiannidou et al., 2009).

Larger disasters have the potential to conduct great destruction and require more planning and action then just sheltering in place. Potential hazards that result in major loss of life and destruction of infrastructure require populations to leave harms way immediately. The threat of man-made or natural disasters disturbing everyday life has created a need for emergency evacuation methodologies to be common knowledge to the public for quick implementation of such procedures (Mannan and Kilpatrick, 2000). In order to be capable of quick response city officials ought to have a plan of action already in place to vacate highly populated urban areas at risk.

Regardless of the type of treacherous occurrence all evacuation procedures require the four steps of evacuation management: mitigation, preparedness, response, and recovery (The Role of Transit in Emergency, 2008). The first step in this process, mitigation, focuses more on long term goals. The practice of mitigation is reducing risk so an event does not become a disaster. This includes engineering buildings to withstand high winds and earthquakes, and not building in flood prone areas. Preparedness is not just the planning before an event occurs but the practice and exercise of such plans.

Warning messages should be tested in advanced to ensure proper communication plans are in effect, not just among emergency officials but to the general public as well. Emergency management teams need to be trained and prepared to carry out duties at emergency shelters and be well equipped. Individual residents also need to have a personal plan in place for family and love ones in case of an emergency. The mobilization of rescue personal to a disaster area is the response portion of evacuation management. Fire rescue, police officers, medical personal, and volunteers need to be able to quickly be on scene to decrease causalities of the disaster. Most response results depend on planning in the preparedness phase. The last stage of recovery begins when all immediate danger has subsided and residents return to the area to resume everyday life again. In some cases it can include rebuilding infrastructure, reemployment, and reuniting with love ones.

Awareness of the affliction caused by possible incidents, growing concerns of evacuation procedures had led to national level action. Government organizations that have been established to address evacuation procedures include the United States Department of Homeland Security (DHS) and the Federal Emergency Management Agency (FEMA). DHS was formed October 8, 2001 in response to the terrorist attacks that took place on 9/11. The main purpose of DHS is to protect the nation from terrorist attacks and help respond to national disasters (Department of Homeland Security, 2009). On March 1, 2003 FEMA joined DHS and assumed the responsibility of assisting local and state governments in preparedness and response to disasters (Federal Emergency Management Agency, 2009). Both DHS and FEMA collaborated to create the National

Response Framework to advise emergency personnel, governmental, private sector and non-governmental organization officials on response procedures.

DHS and FEMA both recognize the importance of all levels of government working together in an evacuation scenario. The National Support Framework is made up of different documents addressing various divisions of disaster response to coordinate operation between agencies. The Framework is composed of core documents, the Emergency Support Function (ESF), Support Annexes, Incident Annexes and the Partner Guides (FEMA). The core documents address the roles of individuals, local, state, and government agencies in the time of an emergency. Different governmental resources are grouped and given defined responsibilities in the Emergency Support Function Annexes, more specifically transportation is focused on in ESF#1. The Support Annexes describe common functions such as financial aspects and volunteers need. The Incident Annexes provide different guidelines based on the type of occurrence (e.g. biological, catastrophic, and nuclear) that requires evacuation. Through this Framework DHS hopes to achieve national awareness of evacuation responsibility on all levels and is optimistic that future evacuations will be successful.

Evacuation planning falls into two different types of time dependent evacuation procedures; short-notice and no-notice. Events such as hurricanes, floods, and wild fires allow city planners and officials 24-72 hours to evacuate threatened areas; these events lead to short-notice evacuations (Chiu et al., 2007). With short-notice evacuations there is a certain time window that allows people to vacate an area safely. Natural disasters can not be prevented but are rather acts of God and pre-impact evacuation is one method to reduce devastating impacts. Having less people in the impact area allows recovery efforts to be improved by not focusing all attention on disturbing medical aid and recovering bodies (Perry, 1979).

No-notice emergency evacuations can result from nuclear power plant explosions, terrorist attacks and other no-notice incidents. City officials need to have evacuation plans readily accessible to emergency and safety personal for instant implementation. These types of evacuations require citizens of a city to depart right away from their immediate location (sometimes not allowing time for people to return to home for other family members or loved ones). An evacuation of this nature places a huge demand on the traffic network system in a very short time interval. In past research it has been found that optimized signal timing can reduce evacuation time and average delay for these types of evacuations (Chen et al., 2007).

The type of evacuation methodology executed is also dependent of the location and size of the area being vacated. The population and infrastructure of a city can differ based on the time period and location of its establishment. For example, areas developed after the invention of the automobile seem to have transportation networks that favor a majority of citizens relying on personal vehicles for their main mode of transportation. Moreover, urban areas tend to have many residents living very close together with varying demographics. In order to efficiently evacuate all the citizens of an area, particular needs of certain groups of citizens need to be taken in to consideration. Current road networks, bridges, traffic signals, and public transit systems of the city ought to be evaluated for evacuation scenarios that best suit the population of the area.

The issue of evacuating special need population has become more prevalent with current events such as Hurricane Katrina (Litman, 2006). The difficulty in evacuating populations with special needs range based on the extra assistance that is needed by that individual. Individuals who do not speak English and can not heed warning messages or evacuation orders. Elderly and physically disabled populations might have a difficult time with mobility and walking to safe zones. Tourist and transit dependent employees do not have vehicles to comply with freeway evacuation routes and need special assistance to evacuate. Documents such as FEMA's CPG-301 and the 109th congress bill S. 1685 emphasize the importance of emergency planning for special need populations (Hutton, 2009).

FEMA recently developed the Comprehensive Preparedness Guide 301 (CPG-301) titled "Interim Emergency Management Planning Guide for Special Needs Populations" (FEMA, 2009). The purpose of this guide is to better assimilate the needs of disabled people, the elderly, and people who do not own personal vehicles in to evacuation plans. In the past (e.g. Hurricane Katrina) the needs of these populations has been over looked (Kiefer et al., 2006; He et al., 2009; Litman, 2006). The guide address how local, territorial, tribal, and state, managers should handle the extra requirements for special need population under evacuation situations. It discusses solutions such as having a registry for such populations, gathering census data, and use of geographic information systems to organize special need demographics.

The federal government has become extremely aware of the urgency to address special need populations in times of disaster. The 109th Congress developed a bill in 2005 that will "ensure the evacuation of individuals with special needs in times of emergency" (Govtrack.us, 2009). The premises of the bill were based on aftermath of Hurricane Katrina. It proposes pre and post planning for special need individuals including low income families, disabled individuals, homeless, non-English speaking persons, and the elderly.

Special need populations such as transit dependent employees and tourists greatly depend on public transportation for mobility. Furthermore, low income individuals and families could only have one mode of travel: public transit. This study will focus on developing a public transit routing scenario to best service special need populations in the downtown core area of the District of Columbia (Washington, D.C.).

1.1 Public Transit in Emergency Evacuations

The aftermath of the terrorist attacks on New York City and the Pentagon on September 11, 2001 demonstrated the importance of evacuation and disaster planning for highly populated urban areas. A large number of citizens are concentrated in these areas especially during workdays creating a vulnerable target for terrorist. These highly concentrated populated areas can lead to a high causality rates if they are not evacuated quickly. Road networks become fully saturated in evacuation scenarios due to a large number of vehicles vacating, utilizing public transit is one possible alternative to improve level of service during evacuation procedures.

Employing different modes of transportation and aid from nearby jurisdictions proves to be very effective in evacuation procedures. For instance, on 9/11 in New York City the "NYCT and the Port Authority of New York and New Jersey-run Port Authority Trans-Hudson (PATH) trains began emergency procedures within minutes of the first strike on the World Trade Center to evacuate those in affected subway stations…" (The Role of Transit in Emergency, 2008). Besides just employing the New Jersey's metro rail, PATH, to evacuate people across the Hudson River, ferries and private boats provided transportation from lower Manhattan to New Jersey (Mbugua, 2006). Furthermore, New Jersey also assisted New York City by providing buses and personnel to shuttle emergency responders to and from the zone of attack. The use of the multi-mode evacuation and aid from New Jersey's public transit system proved implementation of multi-mode transit resources can be crucial in emergency evacuation.

In addition, in Washington, D.C. the use of Metrorail proved to play a vital role in the September 11th evacuation. Immediately following the strike on the Pentagon the downtown core area of Washington, D.C. was evacuated. This evacuation caused an instant gridlock on the road network. Certain officials decided to keep the Metrorail running in order to help evacuate the city. With the Metrorail operating the city was evacuated in a few hours.

Without proper planning public transit systems can falter in the aid of emergency evacuation (Renne, Sanchez, and Litman, 2008). Bus drivers need to be aware if they are required to provide services during evacuations and if so where the location of evacuation bus stops and routes are located. In the case of Hurricane Katrina the public transit system was not fully utilized leaving many citizens behind to weather the storm and the horrific recovery days following the storm. The state of New Orleans did have a plan that incorporates the use of school buses but does not designate who is responsible to use said resource within the plan. Therefore, the school buses were not used for the evacuation of Hurricane Katrina (Nigg et al., 2006). This case proves how vital public transit systems can be in aiding in the evacuation of special need populations at the time of an emergency evacuation.

Several advantages of using public transit modes in emergency evacuation include:

- Vacating larger number of people per trip
- Not having as many personal vehicles clogging roadways
- Minimizing fuel usage for buses along evacuation routes instead of using fuel for numerous of personal vehicles
- Professional drivers in contact with command centers and officials
- Being able to accommodate special need populations

Mastrogiannidou et al. (2009) found employing public transit systems can greatly decrease the amount of evacuation time. The use of buses and light rail can reduce congestion on roadways by decreasing the number of personal vehicles. By using optimum routes and stops, transit vehicles can evacuate more people per trip in a timely manner by decreasing the delay time caused by over-congested personal vehicles. Furthermore, bus drivers have familiarity with transporting large crowds and changing routing conditions. On a regular basis transit operators cope with lane closures due to accidents and weather conditions. Transit facilities also have experience in operation during special events such as concerts, sporting events, and other dealings that draw large crowds (Scanlon, 2003).

1.2 Research Goals

The main goal of this research is to evaluate different evacuation procedures for special need populations from large urban areas in a time of a no-warning emergency utilizing current public transit systems. For the purpose of the study special need populations will include, but are not limited to, people with physical disabilities, senior citizens, non-English speaking populations, residents and employees without vehicles, and tourists. The specific objectives that will be completed in order to reach this goal are as follows:

- Propose optimum locations for evacuation bus stops
- Construct a realistic microscopic simulation model of a transportation network
- Reduce evacuation time for public transit vehicles through optimum bus stop locations

A major part of Washington, D.C. being evaluated for this research includes one of the busiest Metrorail stations in the metropolitan area, Gallery Place, Chinatown station. This only one of the few WMATA Metrorail stations that acts as a stop and transfer station for three different lines; the red line, the green line and the yellow line. The busy station is located in the center of downtown on H St NW and 7th St NW. The location of this station attracts many individuals to engage in its transportation services. Being in the heart of the downtown core of the District many workers have places of employment near the station. In addition, it is walking distance from many local tourist attractions: the National Mall, The Washington Monument, the White House, and the Washington Convention Center. A terrorist attack at this station could have devastating effects.

The current infrastructure and public transportation systems presently in place in Washington D.C will be utilized to evacuate the entire population of the core downtown area. All the evacuation scenarios are to ensure that populations with special needs are evacuated as well. Through the use of computer modeling different emergency evacuation methodologies and scenarios will be assessed. Emergency evacuations are becoming more common place in this day of age and metropolitan planning organizations as well as transportation engineers are assessing these new planning requirements especially as in this case of our nation’s capital.

2 LITERATURE REVIEW

To develop a methodology to evacuate special need populations in time of emergency evacuation an extensive literature review was conducted. The main topics that were focused on for the literature review consisted of micro, meso, and macro simulation, emergency evacuation methodologies, public transit systems, special need populations, and current evacuation plans in place for Washington, D.C. In the following chapter, selected found literature regarding each of these topics is discussed.

2.1 Simulation Models

Transportation networks can be evaluated on three different levels depending on the purpose of the analysis. These three different spatial scales consist of microscopic, mesoscopic, and macroscopic. Based on the type of experiment conducted each of the computer analysis levels has its advantages and disadvantages (Burghout et al., 2005). As traffic computer simulations evolve hybrid models are meshing components from several different models to better represent real traffic networks (Lerner et al., 2001; Burghout et al., 2005)

Macroscopic simulation platforms simplify the model by representing traffic as a continuous flow and applying hydrodynamic and fluid flow formulations (Lighthill and Whitham, 1955). These models require less time to calibrate and are also less likely to experience errors due to minimum number of inputs and low sensitive nature of the model (Burghout et al., 2005). Because of the simplicity of macroscopic models they are not able to accurately represent complex roadway geometries and detailed traffic control and management systems (Owen et al., 2000). Macroscopic evacuation simulation models prove to be effective for larger areas such as hurricane prone coastal regions. In a macroscopic study conducted on Virginia Beach, VA the tool, MASSVAC, evaluated different operational strategies to evacuate the costal regions under hurricane and flood conditions (Hobeika, 1985). Beyond just the purpose of hurricane evacuation planning macroscopic models can be used to educate planners on how evacuation in one specific area will affect the surrounding road networks. Macroscopic models prove to be helpful in transportation planning, larger networks, and long simulation runs (Burghout et al., 2006). A macroscopic scale will not be used in this model taking into account the level of detail and inputs of the network.

The newest scale developed in transportation simulation is the mesoscopic level. This scale encompasses certain characteristics from both micro and mesoscopic models creating a middle scale of analysis. It models individual car behavior not by the behavior of the previous vehicle but by using traffic density relationships and flow characteristics (Lerner, 2001). Vehicles are represented as individual entities but the characteristics of the vehicle such as lane changing and car following are generalized. With this loss detail of the vehicle's exact behavior a level of realism is lost in the model (AIMSUN User Manual, 2008). "Mesoscopic models model individual vehicles, but at an aggregate level, usually by speed-density relationships and queuing theory approaches" (Burghout et al., 2005). For example, mesoscopic simulations model lane changing behavior using density of the lanes rather than detailed driver interaction (Lieberman, 1997).

Microscopic scales prove to be more effective for smaller road networks given the large amount of inputs needed to build and calibrate the models (Mastrogiannidou, 2009; Chiu and Mirchandani, 2008; Lerner et al., 2001). Microscopic simulation platforms have the capability to model individual car and driver behavior in a more concentrated manor; vehicle and driver interaction such as lane changing, response to traffic incidents, lane merging slow down, and reactions to change in the road geometry can be analyzed (Burghout et al., 2005). Evaluating evacuations at a microscopic level illustrates how drivers react to street closures and bottlenecks (Jha et al., 2004). With more detailed results of how drivers respond in emergency evacuations, planning for these situations becomes more accurate. Through the microscopic portion of our model planners in Washington, D.C. will have a better understanding on how to evacuate special need populations with the use of buses and metro rail.

As transportation simulation software becomes more advanced a hybrid system incorporating more that one scale is becoming more common place. Di Gangi and Velonà (2009) were able to prove through their multimodal evacuation approach, “The comparison between experimental data and simulation results show how the usage of appropriate simulation models can realistically reproduce user behavior and then how such models can be used as a support for drawing up effective evacuation plans.” Incorporating both meso and microscopic levels of simulation allows for advantages of both analysis levels to improve emergency evacuation planning. When a hybrid model is used the microscopic scale of simulation is performed on an area of particular interest while a mesoscopic level of analysis is conducted on the surrounding area (Burghout et al., 2005).

This study uses a hybrid system of analysis to evaluate different evacuation procedures of the public transit system in Washington, D.C. The size of the core downtown road network will require a mesoscopic base simulation for analysis. In order to reduce evacuation clearance time bottlenecks found within the network will be further analyzed using a microscopic level. Moreover, because buses can evacuate larger number of special need populations than cars, this study will use a microscopic approach on road segments that contain higher bus traffic.

A study that utilized a hybrid simulation platform of micro and mesoscopic analysis was performed by Coolahan et al. (2009). In their study they employed the Traffic Simulation System AIMSUN NG 6.0 to perform microscopic and mesoscopic simulation on the Baltimore, MD road network in the case of a smallpox release. Microscopic investigation was performed near 16 local hospitals in the metropolitan area. Through the hybrid model they studied the effects of signal control, network origin-destination travel route/times and redistribution effects when people started traveling to hospitals for smallpox treatment.

2.2 Evacuation Methodologies

The type of evacuation methodology that should be used for an area greatly depends on the road network and type of emergency. A wide-ranging literature review was conducted in order to find the best evacuation methodologies that should be applied to this case study. Chen and Zhan, 2008 conducted an agent based modeling study on three different types of road networks (a grid network, a ring road structure, and a real road network based on the road structure of the City of San Marcos, Texas) proving that, "there is no evacuation strategy that can be considered as the best strategy across different road network structures and the performance of the strategies depends on both road network structure and population density." For the purpose of this study only one type of network, the road structure of Washington, D.C., is used to find the shortest evacuation clearance time implementing different public transit strategies.

In 2009 Degnan et al. used one road simulation network to evaluate and compare several different types of evacuation methodologies. The four main strategies included nearest exit, reference, management and staged. The analysis was based on three different measure of effectiveness: evacuation time, total travel time and lost vehicles. The evacuation methodology reference scored the lowest with the other three methodologies yielding close results.

Different evacuation methodologies reviewed for this study include staged evacuation, contraflow, and corridor evacuation. In staged evacuation the endangered area is divided in to sections and evacuated one section at a time corresponding to some set time interval. The first area evacuated is the area that requires the most time to reach the safe zone or will experience a higher level of risk during the emergency. Staged evacuations prove to be very effective for largely populated urban areas but require ample warning time to implement (Chen and Zhan, 2008; Liu et al., 2006). In 2009, Noh et al. successfully simulated a flood evacuation on the Phoenix, Arizona area using staged evacuation. They divided the downtown area by 5 different contours established on their proximity to the river. The contour segments were evacuated in 30 minute intervals leaving the roadways uncongested until the forth and fifth contours were evacuated. Given that staged evacuation requires adequate warning time to vacate separate segments in staggered timing it will not be exercised in this study.

Contraflow is a method that uses all the lanes in a road segment to move all traffic in one direction. Contraflow increases capacity of the road network resulting in reduced congestion and evacuation time but also requires preparation time to enforce (Tuydes and Ziliaskopoulos, 2006). The evacuation procedure of contraflow is still fairly new in evacuation research doubts of its effectiveness are still present (Theodoulou and Wolshon, 2004). Lim and Wolshon (2005) state that contraflow has only been employed twice and actual field data is lacking to prove the robustness of simulation models. Contraflow is a methodology that is more so related with short-warning evacuations. Implementation of contraflow in hurricane situations is more realistic because of the several days of warning time. The use of contraflow has mainly been in the southeast portion of the United States in hurricane-prone areas even though it can be applied to other types of evacuation (Alsnih and Stropher, 2006). In a survey conducted by Urbina and Wolshon in 2003 stated that eleven out of the eighteen hurricane threatened states plan to implement some form of contraflow.

The method of contraflow can contain challenges to administer. Police assistance is needed to change traffic direction of lanes and ramps for freeways undergoing contraflow. Furthermore, it is imperative that police drive the new contraflow lanes to ensure that no vehicles are still traveling the normal traffic direction. Drivers tend to maneuver slower on contraflow lanes because of the unfamiliarity of the new driving conditions. With all major roadways moving traffic out of an area the difficulty of having emergency vehicles enter the area arises (Lim and Wolshon, 2005). Based on the unfamiliarity and set up time required for contraflow this method will not be applied to this study's evacuation methodology.

Yue Liu et al. (2008) performed a corridor-based evacuation of Washington, D.C. assuming a terrorist attack on Union Station and only evacuating the six surrounding TAZ. Using a GIS-based input module they were able to determine the amount of flow on surrounding evacuation corridors. Currently the evacuation routes for the District of Columbia consist of 19 corridors that start in the downtown area and extend to the Capital Beltway or I-495 (Emergency Transportation Annex, 2009). Our study incorporates these routes for personal vehicle traffic. Going a step beyond what has been evaluate for Washington, D.C. our study will find an efficient way to employ public transit to evacuate special need populations.

2.3 Public Transit

In a majority of metropolitan areas the public transit system is greatly depended on by citizens. Inhabitants and visitors use public transit to get to work and go about other daily activities. Public transportation plays an important part, "providing a transportation option for those without access to a motor vehicle, as well as providing a travel alternative to commuters in order to decrease stress on current infrastructure." (Murray et al., 1998). With public transit already playing a key role in metropolitan and urban life it can be seen why it has been implemented into evacuation procedures.

Evacuating populated urban areas introduce new challenges to current infrastructures (Kendra et al., 2008). Urban areas tend to be heavily populated given the amount of spatial area causing severe congestion on roadways in a time of evacuation. In 2006 Litman claimed that a single highway can typically accommodate about 2,000 vehicles per hour. During a mass evacuation this number is reduced due to an overload of vehicles and weather. Therefore, if the number of vehicles is reduced to 1,000 and each vehicle has an average of 2.5 passengers a four lane highway can evacuate 10,000 people per hour and if the inbound lanes are reversed 20,000 passengers. If the evacuation zone is comprised of 1 million residents it would approximately take 50 hours to vacate the area by vehicle alone (Litman, 2006). With the use of public transit the evacuation time can be reduced by serving a larger amount of people per trip.

Studies focusing on communal transport, such as buses, to aid in mass evacuation for largely populated areas are staring to become more common after the effects of Hurricane Katrina and Rita (He et al., 2009). When using buses for evacuation purposes the main goal is to minimize the delay and the distance a bus has to travel in order to maximize the amount of trips the bus can make in and out of the network (Johnston and Nee, 2006). He et al. (2009) proposed a hybrid Artificial Neural Network composed of a general algorithm and climbing method to solve a location-routing problem for transit-dependent residents. They ran two scenarios a one-staged and a two-staged transit evacuation using buses for Gulfport, Mississippi. Our study will not be incorporating a staged evacuation procedure but will not rule out buses making a round trip to pick up more evacuees.

Terrorist are aware of the vulnerability of public transit systems and have begun to target them directly. In the 1980's several terrorist attacks were conducted on buses and bus stations located in Israel and Pakistan (Rabkin et al., 2004). With time and advancing technology terrorist attacks on public transit systems are becoming more severe and a larger threat. For example, the 2004 multiple train bombings in Madrid, Spain resulted in 191 causalities and many more injured (Rabkin et al., 2004; BBC, 2004, CNN, 2004). The city of London experienced an attack on their subway systems that left the city paralyzed for more than three days showing the impact that terrorist attacks can have on public transit systems (Elmitiny et al., 2007).

Bus, rail, and metro station are attractive targets for terrorists because of the large congregation of passengers such as a crowded bus with standees, or a downtown subway platform at rush hour (Rabkin et al., 2004). Other than just the crowds that generate a terrorist's focus the public transport system can supply the means or the ends of a terrorist attack. In the case of 9/11 terrorist used an airplane in order to cause mass destruction; using the airplanes as a means to conduct their terrorist attack. When the IRA (Irish Republican Army) conducted bombings on tunnels and bridges in England and Northern Ireland normal transport operations were disrupted and caused economical lost demonstrating how terrorist attacks on transport systems can provide an end to relay an aggressive message (Taylor, 2006).

2.4 Special Need Populations

After the disastrous event of Hurricane Katrina it became patently obvious that proper planning is necessary for special need populations (The role of Transit in Emergency Evacuation, 2008; Houston 2009; Sorensen, 2006). The results of Hurricane Katrina prove that public officials had no effective plan in place for residents that required special assistance to evacuate. It was published in the Institute of Transportation

Engineers Journal in an article written by Wolshon (2002) before the event took place that an estimated 200,000 to 300,000 people do not have access to reliable personal vehicles. The purpose of this study is to ensure that a proper public transit evacuation plan is in place for special need populations of Washington, D.C. in order to not repeat the negative outcomes of the past.

The term “special need populations” does not have a definite definition and can vary from jurisdiction to jurisdiction. There are several different characteristics that can require an individual to need special assistants in an evacuation such as race, age, health, income, and medical (Sorensen, 2006; Cutter 2003). The traits that will determine special need requirements in this study will include: hearing or vision impairment, physical medical disability, use of a medical guide dog, low income, non-English speaking, no access to a personal vehicle, elderly, and tourists.

Hurricane Katina showed that without appropriate planning and execution for special need populations the results can be devastating. The Federal Highway Administration (2009) reports that 25% to 30% of the people impacted by Hurricane Katrina had some sort of disability. Among the causalities of Hurricane Katrina only 14.1% were under the age of 50 (Bytheway, 2007). The results from this disaster are due to special need populations not having the financial means or physical ability to follow evacuation instructions and a planner not preparing for such a scenario this was observed by Litman (2006):

> People who had resources were served relatively well because planners are familiar with their abilities and needs. People who were poor, disabled, or ill were not well

> served, apparently because decision-makers were unfamiliar with and insensitive to their needs.

Buses should be used if large numbers of handicapped or senior citizens are to be evacuated or if the destination is too far to walk (Elmitiny et al., 2007). A solution to integrate special need populations in emergency evacuation planning and preparedness in this research will incorporate the use public transit.

Qin (2009) used a genetic algorithm to solve the location allocation problem of public transit stops for social vulnerable populations in New Orleans, Louisiana. This study analyzed the priority of vulnerability on a census block level. The centroids of the census blocks were then used to calculate travel time to the nearest evacuation pick up location. The evacuation clearance time using the new optimum public transit stop produced a lower time than just using arbitrary public transit stops. This research will mimic Qin's research by obtaining demographic information on a census block level, but will not use a genetic algorithm as an optimization tool. This research will utilize linear programming in order to find the optimum bus stop locations for special need populations in downtown Washington, D.C.

3 CASE STUDY

For this study the downtown core area of Washington, D.C. was chosen to be analyzed. In figure 1 it can be seen that the District of Columbia has boarders that resemble a diamond shape, except for on the west side of the District where the boarder is defined by the Potomac River. The exact case study area constructed within the simulation platform is represented by a rectangle located in the center of the city incorporating the White House, the National Mall, and the Washington Convention Center. The challenges faced in evacuating this specific area incorporates the large diverse urban population, prestigious governmental buildings, complicated road network, and significant quantity of population depending on public transportation. Reported by the U.S. Census Bureau the District of Columbia had a population of 591,833 in the year 2008. On weekdays this figure can increase by 72% with about 410,000 people entering the city for business purposes (Longley, 2005).

Established as the nation's capital, the city houses many important governmental buildings, monuments, and congressional meetings. Additionally, Washington, D.C. is the home of the president and most of his elected officials who hold great responsibility and decision making positions for the nation. The headquarters for the U.S. Department of Defense is located in the Pentagon building in Arlington, Virginia which is just minutes away from downtown Washington. The capital also attracts many tourists from all over the world who want to see and experience the history in this monumental city. Tourist attractions range from the Washington Monument, Smithsonian Museums, the Capital building, Mount Vernon, The National Zoo, Old Town Alexandria, Dupont Circle, and etc. (Cooper, 2009).

Located within the study area is one of the busiest Metrorail stations of the Washington, D.C. metropolitan area: Gallery Place Chinatown Station. In 2006, the station had approximate passenger traffic of 7.5 million. Chinatown station attracts large crowds because of the multiple public transit modes available at the station and the large area those modes service. This transfer station services the green, yellow, and red Metrorail lines daily as well as several bus stops for Metrobus. The red line covers a majority of the area north of downtown Washington. It extends far in to the north and northwest with stops located in Shady Grove and Glenmont Maryland. The yellow line has a stop as far south as Huntington, Virginia. All three of these lines contain stops that are located way past the Capital Beltway in opposite directions showing the magnitude of customer service area for the Metrorail mode solely. In addition to just Metrorail access the station also has at least eight Metrobus stops located within a fourth of a mile walking radius. To accommodate large crowds the station has three separate entrances and exits for passengers.

Developing effective emergency evacuation plans for Washington, D.C. is imperative given its importance and vulnerability. Terrorist are aware of the large crowds drawn in to the city for business or pleasure purposes. If trying to make a statement terrorists can surely get noticed conducting an attack on the nation’s capital.

Figure 1 Case study area (Google Earth)

3.1 Washington Metropolitan Area Transit Authority

The nation's capital has one of the most efficient public transit systems in the country operating under the Washington Metropolitan Area Transit Authority (WMATA). WMATA was first created in 1967 in an interstate compact between

Maryland, Washington, D.C. and Virginia. The Washington Metropolitan Area Transit Compact joined public and private transit companies in its jurisdiction in order to have an efficient regional transit service. WMATA is comprised of Metrobus, Metrorail, and newly added MetroAccess. The Metrorail service has 106 miles of track and 86 stations through out the Washington, D.C. area. The metro rail system first started being built around 1969 and was able to begin operating in its first phase in 1976. Before Metrorail began operating WMATA obtained four regional bus systems and launched Metrobus in 1973. The Metrobus portion of WMATA is devised of 1,500 buses and operates 24 hours a day, 7 days a week. The newest division of WMATA, MetroAccess, is a paratransit service that began its operation in 1994.

The service area of Metrobus and Metrorail is approximately 1,500 square miles and services about 3.4 million people. WMATA operated the second largest metro rail system in the United States and the sixth largest bus network. In the fiscal year of 2009 Metrorail and Metrobus had a combined total of 356.7 million trips. The Metrorail services the areas of Washington, D.C., suburbs in Montgomery and Prince George in Maryland, and suburbs of Alexandria, Arlington, and Fairfax county of Virginia. A majority of employees that work in the downtown core of Washington, D.C. use the Metrorail and Metrobus services to get to work from nearby suburb areas. Other than just for business purposes, millions of tourists that visit Washington, D.C. every year enjoy the Metrorail experience as well. A map of the Metrorail service area can be seen in figure 2.

Underground rail make up about 50.5 miles of track with 47 stations will the other half of the track is surfaced with 33 stations. The remaining 9.22 miles of track are aerial and have six stations. On the 106 miles of track Metrorail has several different train lines running simultaneously. The blue, green, yellow, orange, and red line all service different stations within the operating boundary areas. Each line has a train size ranging form six to eight cars in length. The operating fleet of the Metrorail is comprised of five different types of cars; Rohr 1000 series, Breda 2000/3000 series, Breda 4000 series, CAF 5000 series, and the Alstom 6000 series. Each of the cars has the same dimensions of 75 feet long and 10 feet wide.

Figure 2 Metrorail map of Washington, D.C. (WMATA, 2009)

A majority of Metrorail stations are located within the District of Columbia and extend to suburbs in surrounding Virginia and Maryland counties. There are nine transfer stations which allow riders to alter between different train lines, giving passengers maximum maneuverability throughout the city. Operational hours of the light rail system

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differ by day of week. On weekdays trains start operating at 5 a.m. and terminate at midnight providing a very convenient transportation mode for workers commuting in and out of the city. The metro has extended service hours on Fridays and Saturdays until 3 a.m. but does not begin service until 7 a.m. on weekends. During rush periods of service the length of time between trains is approximately six minutes. This time interval between train arrivals can be stretched to twenty minutes during evening hours. Trains operating speed can reach a maximum of 59 mph but average 33 mph with stops.

Another public transportation mode which services the city is the Metrobus system. The entire service area encompasses 319 routes on 174 lines. There are a total of 12,227 bus stops with WMATA owning and operating 597. The buses used by WMATA have the capacity to seat on average 40 passengers.

All buses and trains used by WMATA meet ADA (Americans with Disabilities Act) guidelines. Buses in the Metro fleet are capable of lowering floor ramps or are equipped with lifts making them handicap friendly. Priority seating is provided for senior citizens and people with disabilities right behind the bus operator. Currently, about 70% of the buses owned by WMATA have audio stop broadcasts and digital visual text signs announcing major transfer intersections and stops.

Metro trains follow suit to metro buses and also provide priority seating from disabled customers and use visual signs to display stops. Moreover, metro stations as well as metro trains in addition comply with ADA standards. Fare vending machines located in stations provide a lower panel for customers and instructions in several different languages, raised text, brail, and audio. A majority of escalators located in metro stations have bright painted strips located on steps for patrons with low vision and all stations are furnished with elevators. WMATA has introduced gap reducers between the train cars and platform reducing space making moving on and off the car more manageable for physical disabled customers.

WMATA has recently opened a new transportation division that caters particularly to passengers with physical disabilities called MetroAccess. This sector of WMATA provides a door-to-door paratransit service to passengers whose disabilities prevent them from using regular bus or rail services. Customers do need to meet requirements set by WMATA in order to be eligible for this specialty service and receive a MetroAccess ID card. Trips are scheduled through WMATA's website or automated phone service and must be scheduled 24-hours in advanced. MetroAccess is available in the same area and time periods that Metrorail and Metrobus operate.

3.2 Washington, D.C. Current Evacuation Plans

Current evacuation plans for Washington, D.C. is composed of 19 major corridors exiting the city leading to the capital beltway I-495. Secondary route choices have also been designated by DDOT allowing for flexibility to transfer from one primary exit route to another if needed. These routes are defined in the evacuation map of Washington, D.C. in figure 3. Pennsylvania Ave (runs diagonal through downtown from northwest to southeast) is designed to act as a dividing line to which direction the general public will vacate Washington's core downtown area. According to current evacuation plans found in the District Response Plan all people north of Pennsylvania Ave will access the evacuation routes traveling north, east, and west out of the area while people located south of the dividing line will use southern evacuation routes. This division is due to no traffic being able to cross Pennsylvania Ave during an evacuation. In addition, a portion of Pennsylvania Ave will be blocked off to vehicles between 23rd St NW and 3rd St NW and only pedestrian traffic will have access to this portion of roadway.

The signal timing plan currently in place for evacuation purposes consists of two separate parts. Intersections along the corridor routes will be set to 240 second cycles giving the evacuation routes a majority of the green time. All other signalized intersections will run on PM rush hour timing. Intersections along evacuation routes that do not operate on the 240 second cycle will flash yellow on main streets and red for arterial side streets (District Response Plan, 2006).

The District has also prepared for the complete shutdown of the Metrorail in case operations are disrupted or if shutdown is needed for safety in case of an emergency. According to the District Response Plan the loss of Metrorail "would be catastrophic for the transportation system… and will need to be a District priority during response and recovery". If the Metrorail experiences a shutdown bus service will be extended to partially compensate for the rail loss. Furthermore, the District encourages vehicle-less non-residents to explore other transportation options: carpooling, taxi, and walking.

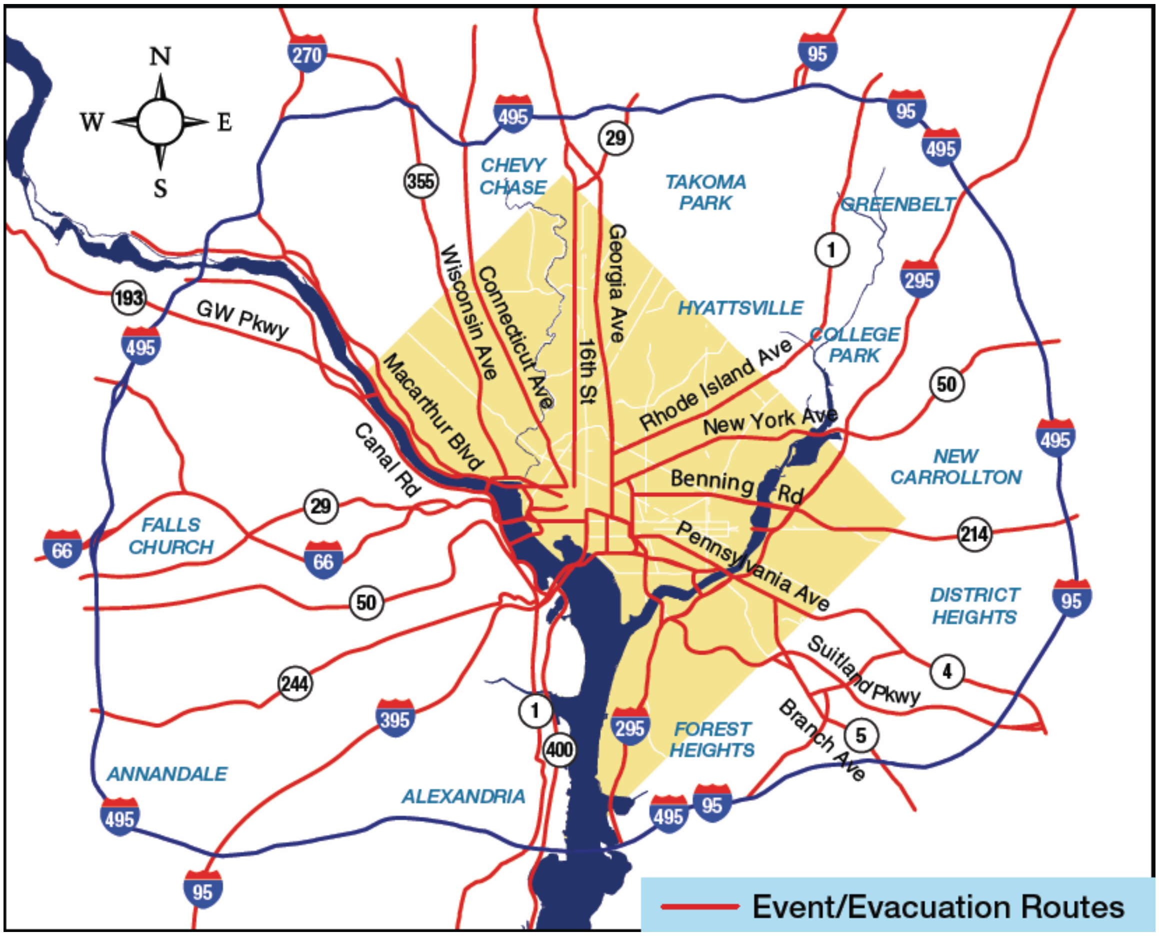

Figure 3 Evacuation routes for District of Columbia (DDOT, 2002)

3.3 Road Network

A microscopic simulation model of Washington, D.C. core downtown area was constructed in the simulation platform AIMSUN NG 6.0. The construction of the network begins in the west from 23rd St NW and extends east to Capitol St. The simulation model is also bounded by P St to north and Independence Ave to the south. The extent of the case study area is defined in figure 4. It incorporates 62 traffic analysis zones (TAZ) that are centrally located in the downtown portion of the District. Using satellite images from Google Earth and street view from Google Maps the geometry of the road network was constructed. The road geometry was then validated using centerline ArcGIS shape files provided from the District Department of Transportation (DDOT). The network is comprised of 129 miles of road, 621 intersections, and has approximate dimensions of 2.8 miles x 2 miles. In this document the word node will be used to define all intersections and merges and the word centroid will be used to refer to origin-destination or safe zone centroids. The average lane width of all roads generated within the network was 12.1 feet.

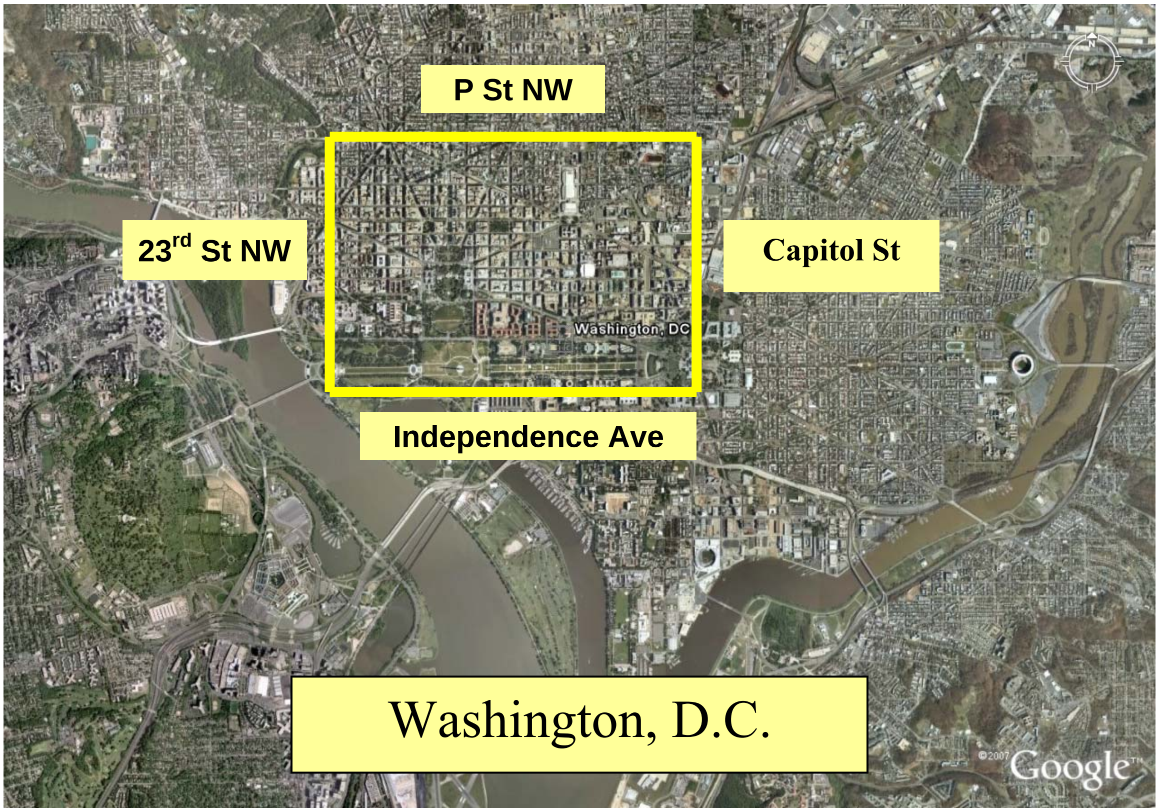

Figure 4 AIMSUN computer model road network (Google Earth)

All signalized intersections located in the computer model were calibrated using Synchro files provided by DDOT. Three sets of signal timing files were collected in total: AM peak hours, Midday-off peak hours, and PM peak hours. The AM peak hour file corresponded to signal timing used for the downtown area between the hours of 7am to

9am. Midday-off peak and PM peak period signal timings represent the hours of operation from 10am to 2pm and 3pm to 7pm, respectively. Mean yellow and red inter-phase time of four seconds was used for signalized intersections located in the model. Several intersections located where pedestrian traffic is heavy (i.e. around the National Mall) had signal phases built in for pedestrian crossing.

To calibrate and validate the road geometry and signal timings of the computer model everyday background traffic was used. Everyday traffic demand was provided in origin destination matrices and was validated using 2006 traffic counts from the DDOT. These every day origin destination matrices received from the agency under the Metropolitan Washington Council of Governments (MWCOG), the National Capital Region Transportation Planning Board (TPB). The everyday matrices were used to produce background traffic on the model before the evacuation commences and validated the model when compared to traffic counts. The origin-destination matrices were given in the computer software package, Cube Voyager. The entire trip table matrices of the entire Washington metropolitan consisted of 2191 rows and 2191 columns to represent all 2191 TAZ located within the Washington Metropolitan area.

Each origin-destination matrix provided from the National Capital Region Transportation Planning Board was categorized based on mode. There were a total of five different modes that made up the entire everyday traffic demand. The first three tables were combined to find the total trips of cars in the network and tables 4 and 5 were used to calculate the number of trips produced by trucks. The five trip tables were categorized as the following:

SOV vehicles

HOV 2 occupancy vehicles

HOV 3+ occupancy vehicles

Medium trucks - 2 axle, 6+ tires

Heavy trucks – all combination vehicles

The travel demand for the evacuation traffic of the network was found by using demographics provided by the U.S. census bureau. Demographic records organized by TAZ were analyzed and manipulated to calculate the amount of vehicles, pedestrians, and special need populations that will need to be evacuated for each zone. The amount of evacuation trips produced was then applied to an inverse distance gravity model to determine traffic assignment.

To enter the origin-destination matrices the production/attraction centroids for each traffic analysis zone were first strategically placed within the model. The safe zone centroids were then created at the end of each major corridor evacuation route exiting the downtown core area. The centroid configuration allows for a 71 x 71 origin-destination matrix to be used to produce a traffic demand. The simulation platform used for this research has the ability to store several different trip matrices using the same set of centroids located within the model.

Bus and metro routes were obtained from the WMATA website, discovering that over forty different bus routes operate within the case study area. Each route was entered to the network with all corresponding bus stops and timetables for the time interval of the simulation run. One notable route is bus route 80 that travels all the way east to west across the downtown area stopping at major transportation hubs such as Union Station, Chinatown station, and the White House. The everyday route for bus line 42 is shown in figure 5 and has several stops at Metrorail stations. Routes 13A, 13B, 23F, and 13G all circulate around the National Mall providing tourist with a means of travel to surrounding areas.

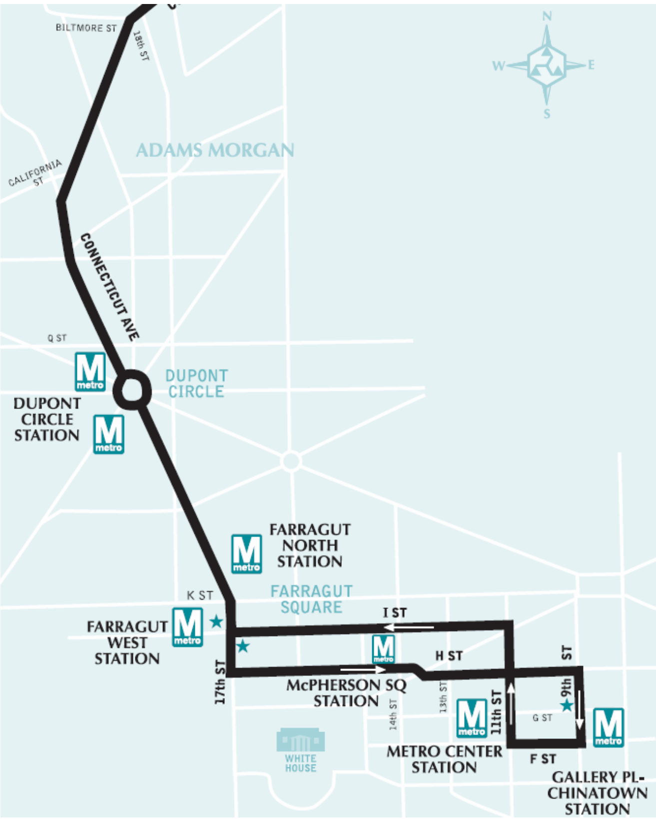

Figure 5 Bus Route 42 (WMATA, 2007)

3.3 Simulation Platform

Popularity of simulation platforms for transportation planning purposes has grown increasingly. Using results from computer models proposals can be validated, surrounding impacts can be found, and cost benefit analysis are more sound (Barcelo and Casas, 2002). Simulation models are able to supply accurate representation of real networks using precise user given inputs and data. When deciding on which simulator to use one should choose a simulator that can meet the requirements of the project (Xiao et al., 2005). The computer simulation platform that was chosen for this research was AIMSUN NG 6.0 professional version.

AIMSUN uses object-oriented simulators and a graphical user interface to produce 2D and 3D animations of the road traffic network. Real traffic conditions for different road networks can be modeled in AIMSUN using certain built-in functions such as lane changing, car following, and gap acceptance (Xiao et al., 2005; Barcelo et al., 2004). In this particular simulator three different scales of traffic analysis can be performed: micro, meso, and macro. Different traffic networks can be evaluated in the software using object features such as segments, nodes, centroids, signal timing, public transport stops and lines, meters, detectors, variable message signs, and vehicle type (AIMSUN Users Manual, 2008).

The simulator has the capacity to model numerous scenarios based on user options. When constructing a network in the platform the user can choose from a selection of road type, vehicle type, travel demand, percent turning, signal length, timing and phases. The procedure used by AIMSUN's microscopic simulator is based off of a large set of algorithms. The algorithms range from headway to dynamic user equilibrium.

3.4 Evacuation Scenarios

Terrorist conceal multiple bombs throughout the downtown area of Washington, D.C. According to Noh et al. (2009) at approximately 11 am during a weekday the population is greatest in downtown metropolitan areas. Therefore, for this research the first two bombs will be detected at that time. The evacuation will commence after two bombs are found in Gallery Chinatown and Union Station. Knowing that the remaining bombs are still located in the downtown core area of Washington, D.C. the entire area will need to be evacuated for safety purposes.

Five different public transit scenarios will be evaluated to determine which scenario is most effective in evacuating special need populations. Each scenario will be based on the maximum number of optimum bus stop locations. Scenario 1 will correspond to the optimum 20 bus stop locations, scenario 2 will correspond to the 30 bus stop locations and so forth for the 30, 40, and 50 bus stop locations. All scenarios have the same number of special need populations to evacuate and will require the same amount of evacuation bus trips. The evacuation bus routes will follow normal operations until the bus stop location. After the bus is loaded with evacuees it will continue along the route until reaching an evacuation corridor. The bus will then proceed to the nearest safe zone using the pre-set evacuation corridors.

4 METHODOLOGY

In order to develop methodologies to deploy public transit vehicles to better incorporate special need populations and adhere to current evacuation plans set for Washington, D.C. different scenarios are modeled in multiple simulations and evaluated. All scenarios assume that the evacuation commences immediately requiring all people to evacuate from current locations and not return home before vacating. Using bus routes and bus stops currently in place for the case study area the best scenario was found to evacuate special need populations. The following chapter will cover the production of trip generation, trip distribution, bus stop location optimization model, and the simulation methodology.

4.1 Origin-Destination Matrices

Considering the large size and specific demographics of special need populations located within the boundaries of the microscopic simulation network, origin-destination matrices were used to produce the traffic demands. The large size of the microscopic network would require many manual hours of labor to input traffic flows and turnings to each individual link. Where as, an origin-destination matrix allows the simulator to specify the origin and destination of each trip, but is dependent on the route choice and dynamic trip assignment of the simulation platform to define the travel path of each vehicle. In an origin-destination matrix, the rows represent the production from each origin while the columns represent the attractiveness of each destination. The trips produced in each area are distributed throughout the network according to the attractiveness of pre-set zones. Through the attraction and production of each pre-set zone the number of vehicle trips can be accounted for. The sum of all vehicles produced will equal the sum of all vehicles attracted, allowing for each vehicle in the network to have a defined origin and a destination. In the case of evacuation all trips are produced within the network zones and are destined to the outer safe zones. The dimension of the matrix is dependent on the number of origin and destination pre-set zones in a given network: for the model used in this research there are a total of 71 centroids that are used to represent origins and destinations; 62 centroids for each traffic analysis zone and 9 centroids for the 9 safe zones. The configuration for an origin-destination centroid for TAZ 33, 29, 24, and 34 is shown in figure 6. The simulation software has the capability to store several different trip matrices using the same set of centroids located within the model. Table 1 illustrates a small portion of the everyday car trip matrix for TAZ 1 through 5. The same origin-destination centroids were used for the evacuation trip matrices.

Table 1: Partial everyday matrix used for car trips

TAZ	1	2	3	4	5
1	34.64	6.57	7.76	3.98	2.47
2	6.54	202	23.65	15.28	7.09
3	7.82	16.55	350.47	20.01	8.05
4	3.98	15.06	12.78	151.23	5.06
5	2.51	7.02	8.08	5.11	26.69

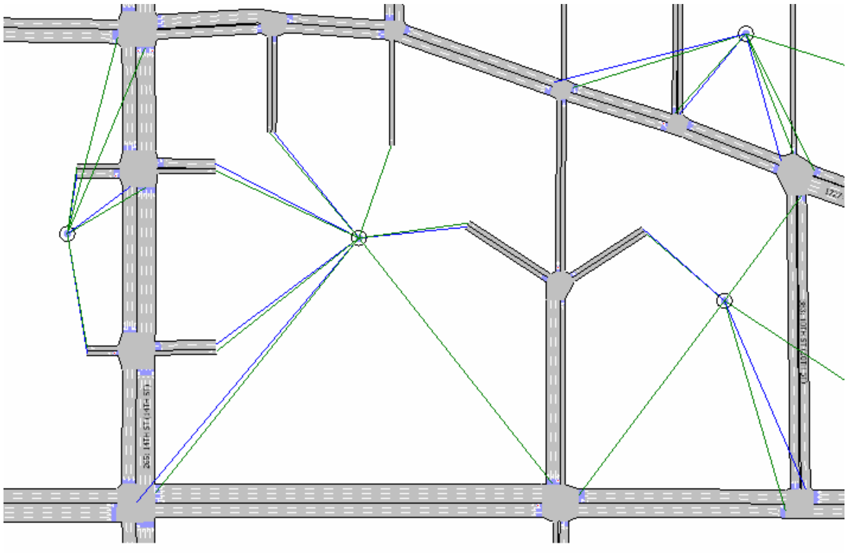

Figure 6 Origin-destination centroids found in AIMSUN network

4.1.1 Background Traffic Demand and Assignment

The everyday trip matrices received from MWCOG had to be manipulated in order to be compatible with the downtown core Washington, D.C. network constructed for this analysis. The given matrices from the transportation planning organization were composed of 2191 traffic analysis zones that included the entire metropolitan area of Washington, D.C. extending into the suburbs of Maryland and Virginia. This research is not focused on evacuating the entire metropolitan area but rather just the downtown core. Because the everyday traffic of the city is also based on trips originating from these boarding outer zones they still must be incorporated in to the background traffic. A method was devised to include these outer zones in the smaller dimension origin-destination matrix to be used within this research's simulation model.

As stated previously the model used for this study employs one origin-destination centroid for each traffic analysis and safe zone. The safe zones are used to represent a safe location a safe distance from the hazardous area and are strategically placed according to current evacuation plans in place by the city. Once the vehicles reach these safe destinations it is assumed that they are a safe distance from the hazard and will proceed to shelters (hotels, friends/relatives, or safe shelters designated by The District, Red Cross or FEMA) until recovery can begin, and are no longer represented in the model. To keep the simulation close to real life conditions, current evacuation routes are used to lead vehicles to safe zones. Therefore, the 9 safe zone centroids are located at the end of road segments that represent each existing evacuation route (set by DDOT) in the simulation model for the downtown area. The safe zone centroid configuration can be seen in figure 7. Only one safe zone centroid is used for the two evacuation passageways M St NW and K St NW due to their close proximity to each other. The safe zone centroids are used to represent a “supervirtual destination for all the evacuation flows” (Chiu and Mirchandani, 2008). The evacuation routes use a corridor-based system to lead all vehicles out of Washington, D.C. to I-495 also known as the Capital Beltway. For modeling purposes the safe zones represent this larger safe area without having to extend the network all the way to I-495.

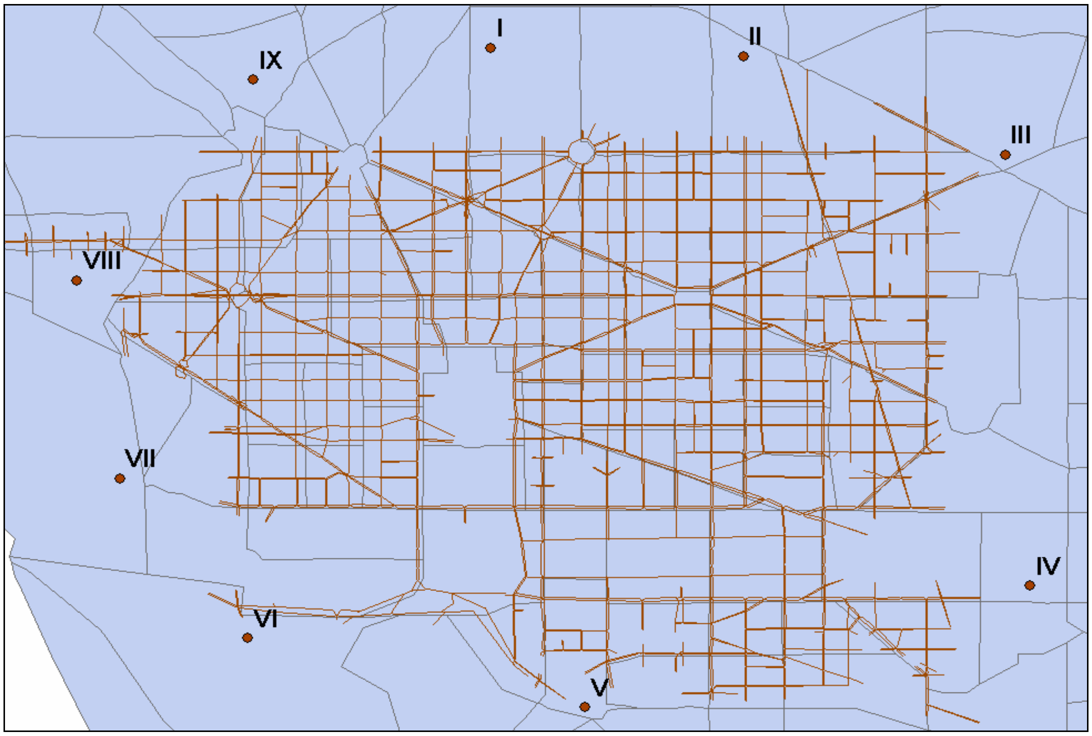

Figure 7 Safe zone centroid configurations

The centroids corresponding to safe zones generated in the simulation model contain two purposes. First, they are used to represent the safe area a safe distance from the terrorist attack during the evacuation. During the evacuation scenarios these centroids do not have any vehicles originating from them but only contain pure attractiveness for vehicle trips. Secondly, they are used to represent the trips originating and destined to and from locations outside of the computer model for the everyday background traffic. As mentioned previously the origin-destination matrices provided by the MPO included trips from zones located outside the computer road network but still need to be represented by the model. Since the safe zone centroids represent an exit to a general safe area outside the network it was assumed appropriate to also use them to represent outside traffic entering and exiting the network for the everyday O/D matrices.

Two origin-destination matrices fabricated from six sections were used in order to accurately represent the everyday background traffic of Washington, D.C. in the simulation platform. The matrices were formed using the same information the local TPB and MPOs utilize for traffic forecasting of the area. One matrix represents the trips generated from cars (background matrix A) and the other matrix corresponds to trips produced by trucks (background matrix B). Both matrices were formed from three separate sections or smaller sub-matrices in order to fit the dimensions of the matrix in the computer model.

Sub-matrix 1A and sub-matrix 1B constitute of all the trips that originate and end within the downtown area inside the computer road network. The size of matrix 1A and 1B is 62 x 62, representing the production and attractiveness of all 62 TAZ located within the network. These matrices were taken directly from the traffic forecasting data provided and did not require and further manipulation. The development of sub-matrix 2A, 2B, 3A, and 3B demanded a more in depth procedure.

The second and third set of trip matrices represent the everyday background traffic of cars and trucks that are either traveling out or in to the computer network built for this analysis. For simplicity, in order to model these trips within the simulation network, the exterior TAZs were grouped together in to nine separate sections and are delineated by the safe zone centroids. To combine the remaining 2129 zones not occupying the virtual network the Thiessen polygon method was utilized. Thiessen polygons are commonly used by civil engineers for hydrologic application. For a given number of spatially distributed points, the Thiessen Polygon Method is capable of producing their respective areas of influence, which in the case of hydrologic applications, is utilized to define the contribution area for a gauging station, and for this application, the contribution area for a safe zone centroid. In this case, a safe zone centroid will be used to represent all the trips produced and attracted from and to the created polygon area. This method was chosen due to Thiessen polygons using a spatial relationship to find relative points that are closest to one point. This allows all the zones closest to one safe zone centroid to be assembled together and have all vehicle traffic correspond to one origin and destination. Thiessen polygons are “mathematically defined by the perpendicular bisectors of the lines between all points” (ET Geo Wizards). Using the Thiessen polygon generation feature of ArcGIS 9.3 and the nine safe zone centroids, the polygons were created and incorporated all the TAZ trip information provided by the MPO (figure 8).

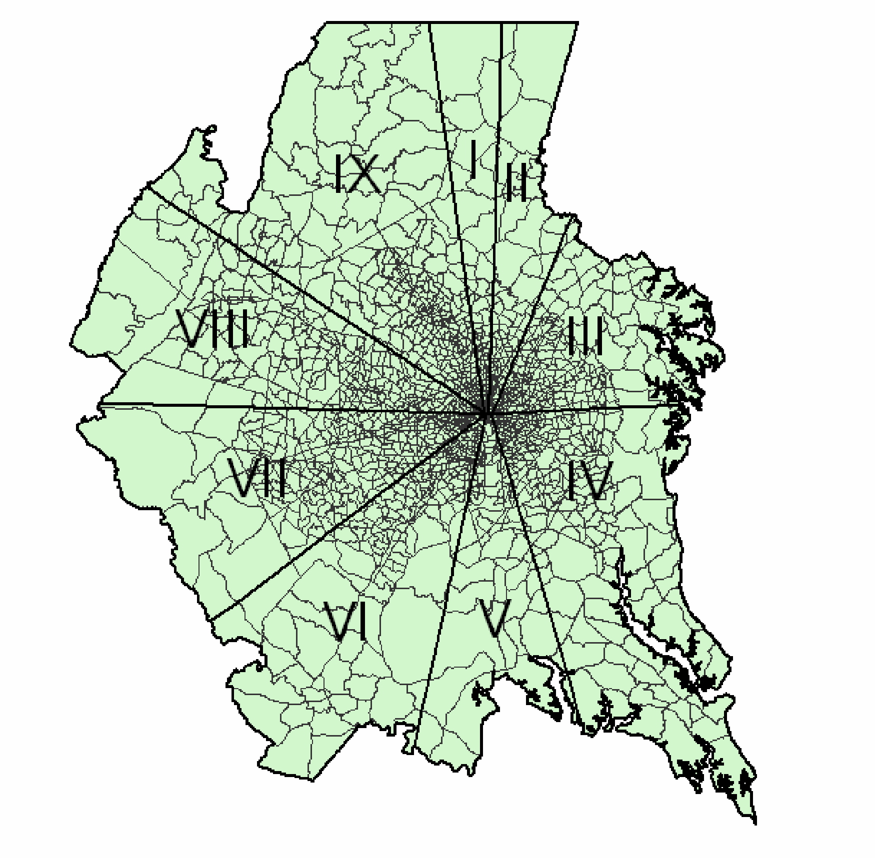

Figure 8 Thiessen polygon distribution of outer TAZs

Several different tasks had to be performed in order to implement the Thiessen polygon method. A traffic analysis zone shapefile, provided by the TPB, was used to find the location of all 2192 zones that corresponded with the origin-destination matrices they furnished. The vehicle trip matrices were divided into 2 categories: cars and trucks. Normally in the Thiessen polygon method the points are connected to find perpendicular bisectors which are then extended to divide the area into polygons. For this research, the Thiessen polygon feature of ArcGIS was employed to generate the Thiessen polygons. The nine unique polygons were labeled according to their corresponding safe zone centroid. The vehicle trips associated with each TAZ was then associated with the safe zone polygon it was located in. Any trips that were produced or attracted to the TAZ are now grouped into the 9 polygons using the safe zone centroids as their origin-destination centroid.

Several traffic analysis zones were divided between two safe zone polygons. To accurately determine the amount of everyday background trips traveling to and from each polygon an area based method was applied in cases where a TAZ is located in more than one polygon (Figure 9 and equations 1 to 3).

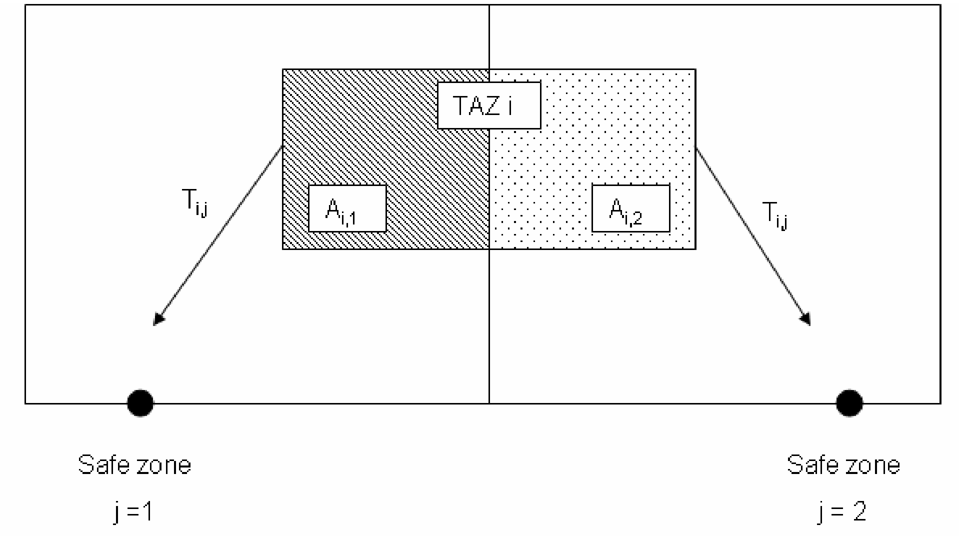

Figure 9 Area based method to develop new vehicle trips from divided TAZ

$$T_{i,j} = \left(\frac{A_{i,j}}{A_i} * T \right) \tag{1}$$

$$T_j = \sum_{i=1}^{I} T_{i,j} \quad j = 1, 2, 3 \ldots 9 \tag{2}$$

$$Ti, j = \begin{cases} 0 & \text{if i} \not\subset \text{j} \\ Ti, j & \text{otherwise} \end{cases} \tag{3}$$

Where,

$T_{i,j}$ = Trips originated in traffic analysis zone i associated with safe zone j;

$A_{i,j}$ = Area of traffic analysis zone i within safe zone j;

A_i = Area of traffic analysis zone i

T_j = Total number of trips associated with safe zone j;

For example, if TAZ 110 lies between polygon VIII and polygon IX the area of TAZ 110 will be calculated twice, once for area lying in polygon VIII ($A_{110,VIII}$) and once for polygon IX ($A_{110,IX}$). This new area is then divided by the entire area (A_{110}) of TAZ 110 to get the ratio area that lies in each polygon. This ratio is then multiplied by the total number of trips (T) in TAZ 110 to find the amount of trips that correspond to each polygon ($T_{i,j}$).

Using the trips now divided into 9 polygons the sub-matrices 2A, 2B, 3A, and 3B could be produced in order to represent outside traffic within the network. Sub-matrices 2A and 2B were generated to represent the production of traffic from outer zones located within the new external polygons traveling to the downtown area. All trips produced from the outer TAZ were categorized based on the Thiessen polygons they corresponded to. This procedure allowed for all vehicle trips originating from exterior zones to be represented in the network using the corresponding safe zone centroids as origin-destination centroids for everyday background traffic. The dimensions of sub-matrices 2A and 2B was 9 x 62 for both car and truck trip production entering the computer model (9 origins associated with 62 destinations). The sub-matrices 3A and 3B represented the vehicle trips exiting the computer network and had dimensions of 62 x 9 (62 origins associated with 9 destination).

Once all six sub-matrices were complete they had to be joined. By joining matrices 1A, 2A, and 3A, the everyday background trip matrix for cars was produced. The sub-matrices 1B, 2B, and 3B were combined to form the everyday background trip matrix for trucks. Trips that originated and are destined from and to zones located out of the computer model were assigned a valued of zero (It is assumed if a vehicle trip is originated and ends outside the network it will not enter the network. This assumption is made based on the majority of drivers wanting to avoid downtown traffic and utilizing the Capital Beltway). Through these trip matrices, the travel demand and assignment for the everyday background traffic was implemented into the simulation computer model and used to calibrate and validate the model and to produce background traffic before the evacuation scenario is initiated.

4.1.2 Evacuation Traffic Demand and Assignment

To obtain legitimate public transit results personal vehicle traffic must also be modeled. In the evacuation scenarios the exiting traffic demand is greatly increased. It is assumed that all people located within the network during the time of the incident must be evacuated using some mode of transport. Because the evacuation scenario takes place in the middle of a workday, certain demographics of each zone needs to be taken in to account to obtain an accurate number of evacuees. Statistics such as the number of employees, residents, and tourists located in each TAZ at the time of evacuation are used to produce the traffic production of each zone.

The goal of this evacuation methodology is to relocate all people located inside the network to safe zones. The safe zones are located outside the network along major roadways that currently act as evacuation routes for the city. The simulation model used for this analysis has a total of nine safe zones. The safe zones are the only zones in the model that produced travel demand. This is due to our study assuming a no-warning evacuation, not allowing people to return home before evacuating. It is assumed once vehicles in the network reach these safe points they are no longer in harm's way and can continue safely to shelters. The traffic demand of each safe zone was obtained based on their attractiveness as a function of the inverse distance between them and the traffic production areas.

The first step in developing the evacuation origin-destination matrices required obtaining the trip production for each traffic analysis zone. Using demographics obtained from the U.S. Census Bureau trip production for personal vehicles in each traffic analysis zone was calculated by the following empirical equations:

$$R_z = E_z + (p_z * r_z) + T_z \quad \forall z \tag{4}$$

$$P_z = R_z * 0.63 \quad \forall z \tag{5}$$

$$V_z = P_z - \frac{P_z * 0.26}{2} \quad \forall z \tag{6}$$

Where,

E_z = people employed in zone z

p_z = population in zone z

r_z = unemployment rate of zone z

T_z = number of tourist located in zone z

R_z = total people located in zone z midday during a weekday

P_z = total number of people in zone z using personal vehicles

V_z = total vehicle production in zone z

According to United States Census the unemployment rate for Washington, D.C. is approximately 9%. This rate was multiplied by the number of residents living in a TAZ to find the number of residents that can be expected to be at home midday on a workday. This number was then added to the amount of employees and tourists located in the same zone. Using equation 4 the total number of people located within zone z midday on a weekday was calculated. Equation 5 multiplies the number of people in zone z by the percentage of people who don't use public transit. Based on the MWCOG weekday planning model about 36% of the population utilizes public transit services in the city. The sixth equation factors in the percent of the population that car pool to work in the city.

The number of people in each TAZ that rely on public transit for evacuation was obtained from further analysis of demographic data. In order to estimate the amount of people without a vehicle, the total number of people using personal vehicles was subtracted from the total number of people located in that zone during the evacuation scenario. For this study it is assumed that special need populations that are able to drive themselves to work can also evacuate themselves in time of emergency. Moreover, using U.S. census data the amount of physically disabled people, elderly, foreign populations, and low-income households in each TAZ was used to give that TAZ a larger priority for bus routing during evacuation.

After the production of vehicles for each TAZ was known, the personal vehicle trips were assigned to safe zones. Human driver behavior is extremely difficult to predict especially in mass emergency evacuations (Alsnih and Stopher, 2004; Degnan et al., 2009). Knowing exactly what paths drivers will take to vacate the area is a very complex procedure. In this analysis the main focus will be on the exit of public transit vehicles such as buses that have a fixed set route for evacuation. To have the road network properly loaded with personal vehicles in order to simulate how well bus routes service special need populations in evacuation, a trip assignment procedure was developed. For this research the assignment of personal vehicles to a particular safe zone was completed following an inverse distance relationship between the origin and the destination, as defined by equations 7 to 14.

$$V'_{z,j} = f(d_{z,j}, V_z, n_j) \tag{7}$$

$$d_{z,j} = \sqrt{(x_z - x_j)^2 + (y_z - y_j)^2} \tag{8}$$

$$V'_{z,j} = \begin{cases} 0 & \text{If } \mathrm{d_{z,j}} \geq \mathrm{d_{max}} \\ f(d_{z,j}, V_z, n_j) & \text{otherwise} \end{cases} \tag{9}$$

$$w_{z,j} = 1 - \left[\left(\frac{d_{z,j}}{\sum_{j=1}^{J} d_{z,j}} \right) * \lambda_z \right] \tag{10}$$

$$w_{z,j} = \begin{cases} 0 & \text{if } w_{z,j} \leq 0 \\ w_{z,j} & \text{otherwise} \end{cases} \tag{11}$$

$$\lambda_z = \begin{cases} 3 & \text{if } n_j \geq 4 \\ 2 & \text{if } n_j = 3 \\ 1 & \text{otherwise} \end{cases} \tag{12}$$

$$R_{z,j} = \frac{w_{z,j}}{\sum_{j=1}^{J} w_{z,j}} \tag{13}$$

$$V'_{z,j} = R_{z,j} V_z \tag{14}$$

Where:

n_j = number of safe zones (j) within d_{max} of zone (z)

$V_{z,j}$ = number of cars produced in TAZ (z) to safe zone (j)

$D_{z,j}$ = distance between TAZ (z) and safe zone (j)

$w_{z,j}$ = “attractiveness” for cars from TAZ (z) to safe zone (j)

λ_z = adjustment factor for each TAZ (z) as a function of the number of safe zones (j) within d_{max}

d_{max} = maximum distance for a safe zone to be a feasible safe zone

x, y = coordinates of z and j

$R_{z,j}$ = “attractiveness” ratio

The distance of each TAZ to all safe zones was found using the centroid of the zone. The centroids of each traffic zone were found implementing Hawth’s Analysis Tools for ArcGIS 9. This was possible due to the fact that a shape file of the polygon TAZ was obtained from DDOT. The latitude and longitude for each TAZ and safe zone centroid were then documented and used to find the Euclidean distance. Using a logical decision rule, if a TAZ is located further than d_{max} (in this case, 1.5 miles) from a safe zone, it was assumed that no vehicles from that TAZ would use that particular safe zone. This model takes in to account that not all vehicles from one traffic zone would all choose to evacuate to the same safe zone (as mentioned previously driver behavior in an evacuation is very difficult to predict and this model allows for driver choice diversity in selecting an evacuation safe zone). Based on the relative distance between origin and destination, the closer a TAZ is located to a safe zone it was implied that more vehicles would use the closer exit in an emergency. In order to accurately depict vehicles favoring a closer safe zone an adjustment factor was applied. Depending on how many safe zone options within a defined maximum distance range, a TAZ had the adjustment factor varied. The more available choices of safe zones a higher adjustment factor was used. The weighted inverse distance was then used to obtain a related ratio between all the distances for safe zone possibilities for each TAZ. This ratio was then multiplied by the total trips produced in the TAZ. Based on the weighted inverse distance ratio vehicles were distributed to all potential safe zones.

The trip distribution procedure presented in the flowchart in figure 10 is proved to be robust based on several commonly made assumptions in evacuation planning. In summary, first, the process takes in to account that not all drivers located in one TAZ will all vacate to the same safe zone. It also assumes that the closer a driver is located to a safe zone the more likely the driver will use that safe zone. Lastly, if the safe zone is an unreasonable distance afar it is safe to assume that drivers from that particular TAZ will not exit the system using the outlying safe zone.

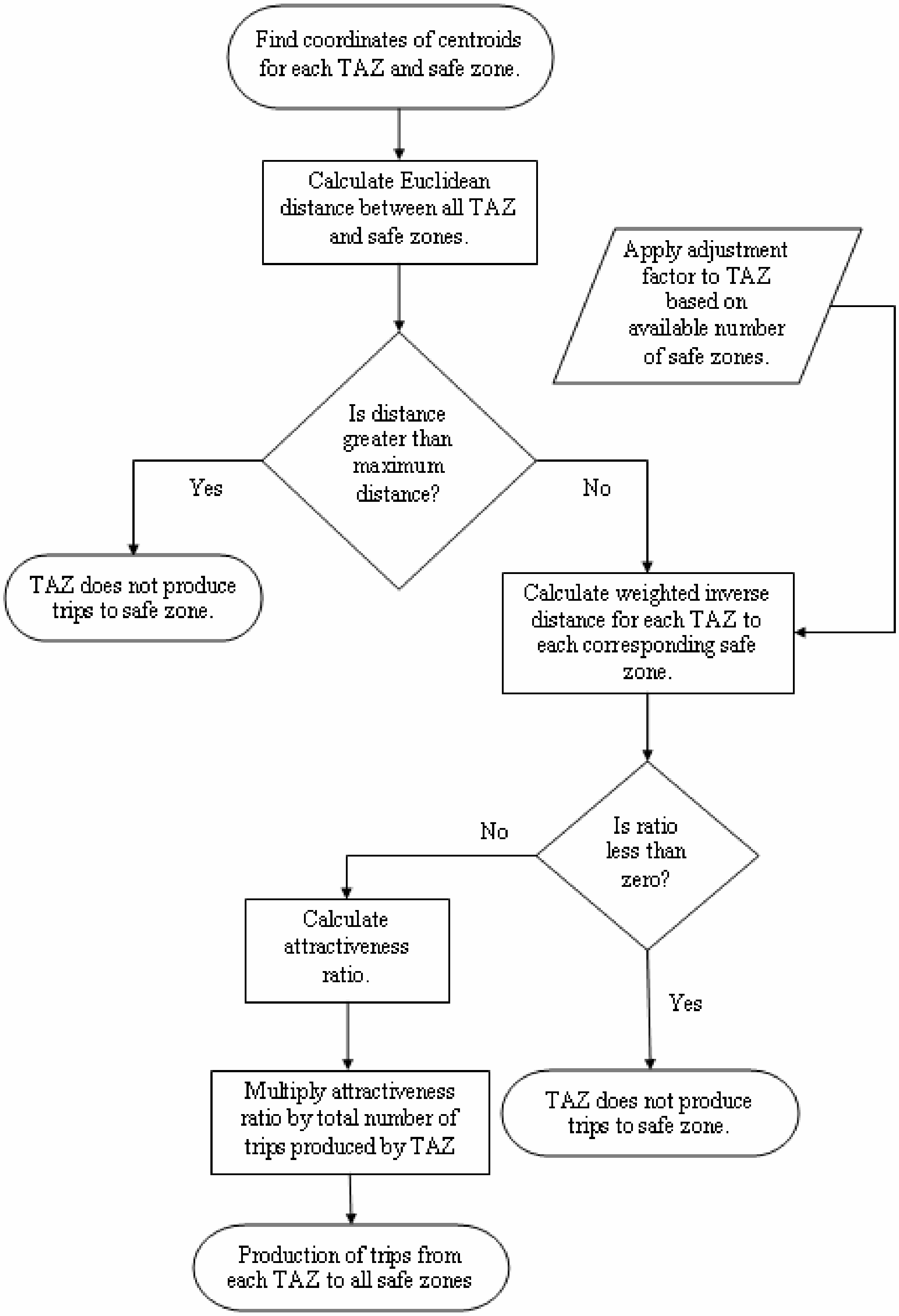

Figure 10 Flowchart of trip distribution procedure

4.2 Evacuation Procedure

No-notice evacuations require large movements of people in a brief time period with authorities receiving little information. In cities and large metropolitan areas the population can be very diverse and require some assistant to heed evacuation orders. The use of public transit can be efficient in such scenarios. This study is aimed at finding the most efficient public transit strategy to evacuate special need populations with a microscopic simulator.

The city of Washington, D.C. offers several different mode options for transportation. One efficient evacuation mode located within the city is the Metrorail. The Metrorail has its own set of tracks and can operate independently of the road network. The Metrorail also has the ability to accommodate more passengers per trip then other modes of transport such as buses or personal vehicles.

If the Metrorail was forced to cease operation the next public mode of transportation will have to be utilized: buses. Taking into consideration that the majority of large urban areas located within the United States do not provide Metrorail or light rail public bus service is commonly the next largest public transit service provided.

4.3 Mathematical Model of Bus Stop Locations

The goal of this mathematical model is to maximize the overall benefit of evacuation bus stop located within the case study area using linear programming with binary variables. The objective function and constraints are presented as follows:

$$\text{Maximize } \sum_{b=1}^{B} \beta_{b,z}\,\phi_{b,z} \qquad \forall\, z \tag{15}$$

Subject to:

$$\beta_b = w_m \sum_{m=1}^{M}\left(\frac{1}{d_{b,m}\psi_{b,m}}\right) + w_v \sum_{v=1}^{V}\left(p_v * \frac{1}{d_{b,v}\psi_{b,v}}\right) + w_l \sum_{l=1}^{L}\left(p_l * \frac{1}{d_{b,l}\psi_{b,l}}\right)$$
$$+ w_e \sum_{e=1}^{E}\left(p_e * \frac{1}{d_{b,e}\psi_{b,e}}\right) + w_o \sum_{o=1}^{O}\left(p_o * \frac{1}{d_{b,o}\psi_{b,o}}\right) + w_s \sum_{s=1}^{S}\left(p_s * \frac{1}{d_{b,s}\psi_{b,s}}\right) \quad \forall\, b, z \tag{16}$$

$$N_z^{\max} = f\left(T_z, A_z\right) \quad \forall\, z \tag{17}$$

$$N_z^{\max} = \sum_{b=1}^{B} \phi_{b,z} \quad \forall\, z \tag{18}$$

$$\sum_{z=1}^{Z} \phi_{b,z} \le \eta \qquad \forall b \tag{19}$$

$$\phi_{b,z} = \{0,1\} \tag{20}$$

$$N_z^{\max} = \begin{cases} \dfrac{A_z}{A_b^{\max}} & if \ \dfrac{A_z}{A_b^{\max}} \ge \dfrac{T_z}{T_b^{\max}} \\[2ex] \dfrac{T_z}{T_b^{\max}} & otherwise \end{cases} \qquad \forall\, b, z \tag{21}$$

$$N_z^{\max} = \begin{cases} 0 & if \quad N_z^{maz} \le \xi \\ N_z^{\max} & \end{cases} \tag{22}$$

Where,

ϕ = binary decision variable

β = benefit of bus stop

b = bus stop

z = traffic analysis zone

N = number of bus stops

m = Metrorail station

d = distance

ψ = distance factor

v = persons that do not own a vehicle

e = persons over the age of 65

l = person with a low income below poverty line

s = physically disabled persons

y = employees

w = weight defined by the decision maker to a criteria category

p = size of special need population

T = bus trips required to evacuate special need population

A = area

ζ = minimum N^{max} value necessary to have a bus stop

η = maximum total number of bus stops for the entire study area

The goal of the objective function is to maximize the overall benefit of chosen evacuation bus stops. Binary variables ($\phi_{b,z}$) are decision variables within the optimization model, utilized to define which bus stops are chosen, however constrained by a maximum number of bus stops per traffic analysis zone ($N_z^{\max}$) and also for the area of study (η). The optimization assigns a maximum number of bus stops to each traffic analysis zone within the case study area (equation 17, 18, 21, and 22). The total number of bus stop locations that can be selected for the area is set be equation 19. The criterion for selecting evacuation bus stops is associated with the weighted bus stop benefit ($\beta_{b,z}$). For bus stops that are selected, the binary variable assumes a value of 1, so that the benefit is added to the objective function, which aims at maximizing the overall benefit.

The benefit associated with each bus stop is based on a function that aggregates distance and population attributes associated with each bus stop (equation 16). The specific benefit of Metrorail stations is solely based on it's inverse distance to a given bus stop. However, for other groups of interest, such as special need populations, the size of population (p) of each special need group will introduce another factor to the benefit function. For instance, a bus stop located near-by a larger population of physical disabled population will have a higher benefit than a lower population for the same given distance.

Taking into considering the different categories of special need populations, the size of each category is require to be normalized in order to accurately represent each group equally. Population sizes can be obtained from census surveys. Depending on how sensitive the decision maker plans on using the optimization model demographic information can be collected based on household, census block, census block group, or census track. Using the maximum population size found the rest of the population sizes was divided by this maximum number to normalize all the data in the category. This procedure allow for each special need category to be represented in a non-biased form.

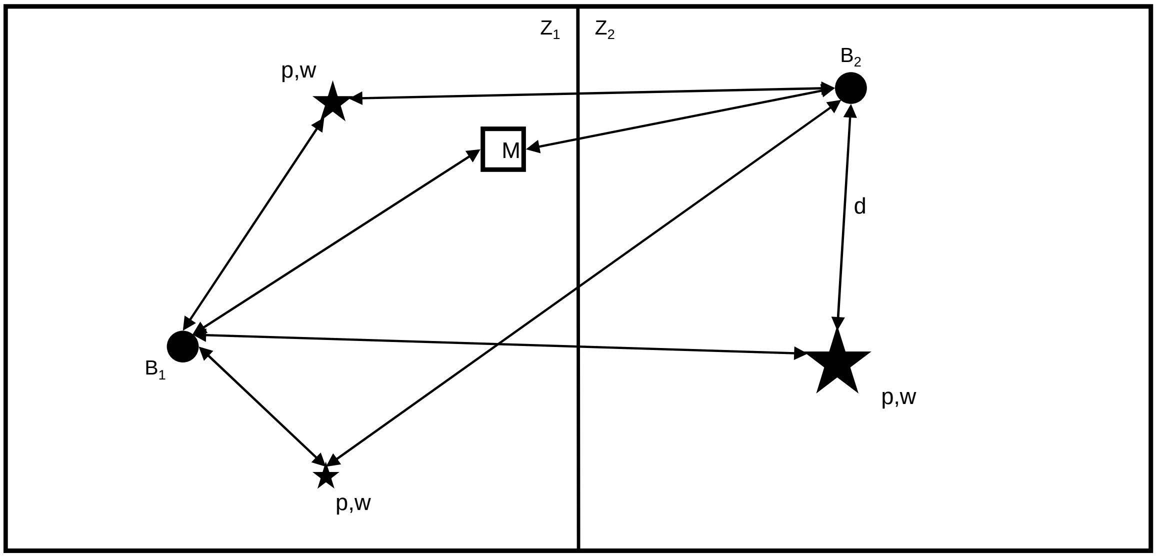

Figure 11 Schematic of optimization model

Depending on how far away an area of a special need group is located from a bus stop a distance factor (ψ) was applied to its associated element on the benefit function. If the group was further than a certain radius from a bus stop a factor of zero is used, indicating that no benefit for that bus stop can be given. A baseline radius can be used for stops that represent a reasonable distance a person will travel to that bus stop. If the area of interest fell within this reasonable radius a distance factor of 1 is defined, so that the inverse distance is not affected by the distance factor. Making an allowance for areas that could be lying just outside of this baseline radius another relaxed radius can be assigned with a larger distance factor. This relaxed radius allows for individuals who are willing to travel a little further than the assumed standard. Giving this area that falls within the relaxed radius the larger distance factor will decrease the inverse distance of the special need population still allowing for some benefit to be included. The effect of this distance factor can be represented by figure 12, where range A corresponds to the baseline radius and range B corresponds to the relaxed radius.

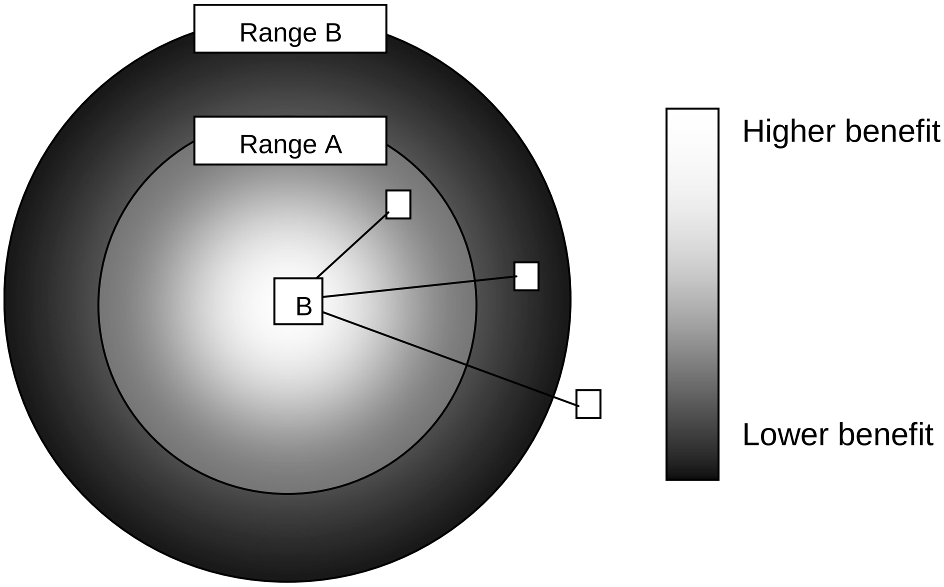

Figure 12 Radius based distance factor

The decision maker has the ability to express their preference towards a specific special need group by defining their importance (*w*). Weight assignment is a subjective task that relies on the knowledge of the decision maker regarding the area of study. Often, a sensitivity analysis is required to evaluate the effect of different weighting schemes on the benefit estimation. Factors accounted for are special need groups that would require extra assistance in evacuation. Eventually, special need groups will demonstrate a certain correlation (i.e. low income individuals not owning a vehicle), requiring the decision maker to evaluate the weight assignment in order to avoid over emphasizing a specific target area.

Other specific target groups such as public transit dependent employees represent a conflicting objective on assigning the locations for evacuation bus stops, as the geographical distribution of this group may not coincide with other target areas/groups. Therefore, the decision maker may express greater preference towards a specific group by assigning a relative larger weight. For example a decision maker planning evacuation bus stops for south Florida might give a larger weight to elderly populations and a much smaller weight to employees. Each geographic region is prone to contain different larger special need populations that would require more assistance in an evacuation scenario stressing the importance on how the decision maker distributes the weights in the benefit function.

In an evacuation scenario using all available bus stops is not a feasible solution based on time constraints. Therefore, a maximum number of bus stops (η) needs to be specified to reduce delay times related to frequent stops (Equation 19). Moreover, the objective function that attempts to maximize the overall benefit of bus stops can lead to the optimum location of bus stops to be clustered in one area that represents the greater benefit value in the whole study area. Equation 18 was introduced in order to inhibit a grouping of bus stops in each TAZ. By dividing the study area in several different traffic analysis zones a maximum number of bus stops can be defined per zone, limiting the number of bus stops in one TAZ area. The maximum number of bus stops that can be chosen for a zone ($N_z^{\max}$) is a function of bus trips required and area of the zone, as defined by Equation 17. This model allows for the decision maker to determine how many trips one bus stop can service. That max number of trips ($T^{\max}$) is then divided by the entire number of trips required for the zone producing the amount of needed bus stops. The decision maker must also decide what the maximum square area will be to require a bus stop. The entire square area of the zone is then divided by this set area and another number of needed bus stops are produced. The formulation then uses the larger of the two values to set equal to $N_z^{\max}$. If the total amount to trips needed and area of a zone do not reach a set value (ζ) it is reasonable to assume that $N_z^{\max}$ can equal 0, stating that no bus stops will be assigned to that particular zone.

Other constraints can be defined to specify the desired number of bus stops for specific TAZ, overriding the function previously described. If one particular TAZ was not an assigned an evacuation bus stop and the need for a bus stop at that particular location is understood by the decision maker an equality or inequality constraint can be declared. For example, for z = 23, no bus stop was originally assigned but by declaring equation 23 as a constraint, three bus stops are enforced:

$$N_{23}^{\max} = 3 \tag{23}$$

Once the total benefit for evacuation bus stops is reached it is important to note the location within the entire case study. The purpose of this model is to maximize the evacuation a specific demographic. The combination of a limited number of available bus stops ($N^{\max}$) and bus stops with low benefit value may cause certain areas not to have any assigned bus stops. The constraint presented in equation 23 may overcome this issue however if a larger area encompassing several TAZ does not contain any selected evacuation bus stops the decision maker may declare another constraint so that the optimization will assign to the referred area a given number of bus stop based on selecting those with a greater benefit. For example, if four TAZ (z=10,11,12,13) have very small special need populations and no bus stop is chosen within this area, as the associated benefit is low compared to other areas, the decision maker can declare the constraint as to still include them within the model:

$$N_{10}^{\max} + N_{11}^{\max} + N_{12}^{\max} + N_{13}^{\max} \geq 1 \qquad \textbf{(23)}$$

If the decision maker finds that the optimum bus stop locations are clustering in one region of the evacuation area and applying constraints such as equation 23 would become to repetitive the area can be spatially divided. By dividing the area into smaller sub-sections, zones can be grouped together and a minimum number of bus stops can be set for the sub-section. This would allow for at least on bus stop per section and a more evenly spatially assignment of evacuation bus stops. Despite the complexity of the given formulation, the model proves to be flexible satisfying the decision maker's needs in evacuation planning for all study areas.

4.3.1 Application to Case Study Area

In this particular research the goal is to maximize the benefit of chosen evacuation bus stop locations that would service a greater amount of special need populations for the Washington, D.C. downtown area. The current amount of bus stops located within the case study area of downtown Washington, D.C. is 392. From the DDOT website GIS shapefiles for all bus stop locations and routes for the entire District of Columbia were acquired. The shapefile were then modified to only include the bus stops located only within the case study area.

Given that equation 21 determines the maximum number of bus stops located in each traffic analysis zone the total number of bus stops located within each zone was found by employing ArcGIS features. It can be seen in figure 13 that certain zones do not contain any bus stops, while other zones contain many bus stops. The bus stops were organized by latitude and longitude coordinates. They were then labeled B1 through B392.

As stated earlier $N_z^{\max}$ is a function of the trips required and area of a traffic analysis zone. A zone with a larger area requires more stops as stated in equation 21. This is to prevent an evacuee to have to walk an unreasonable distance to a bus stop despite that they are both located within the same zone. The maximum area for one bus stop given in this case study is 0.25 mi^2, which according to Sanchez (1998) is normally the maximum amount of distance people are willing to walk for public transit services. Also, if a zone has a very small area but is very populated and requires many bus trips to evacuate, the model will accommodate the larger number of trips with an extra bus stop to provide for the extra trips. The maximum number of trips per bus stop used in this research is 100. This number was chosen through trial and error and providing the best results for this case study.

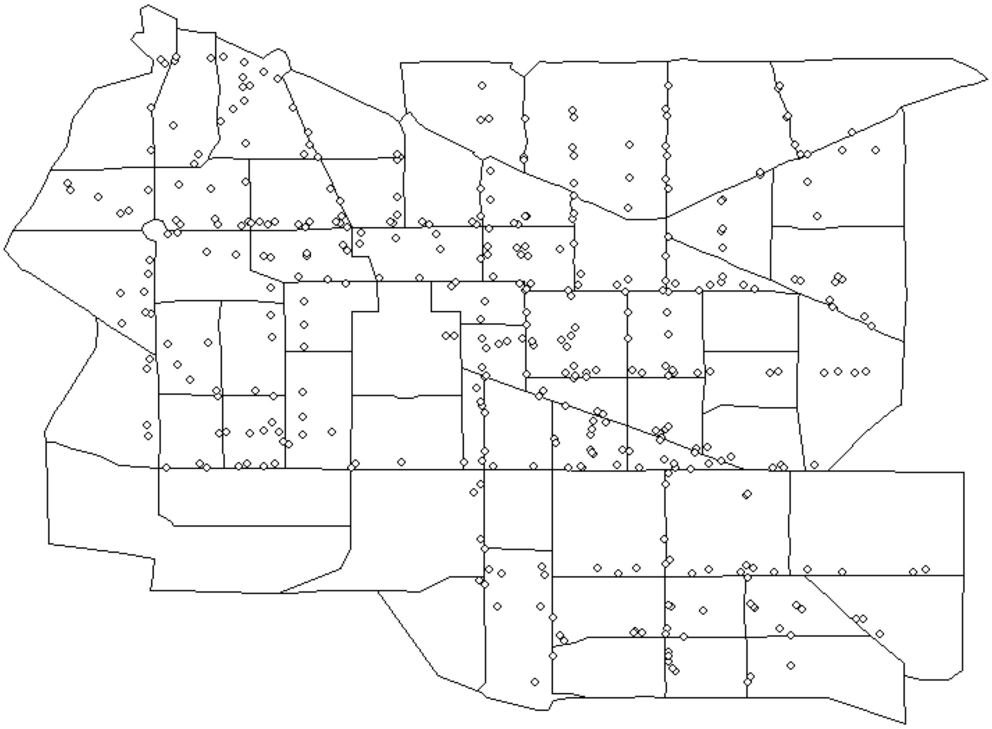

Figure 13 Bus stops within case study area

Originally demographics for the case study area were collected by TAZ. It was soon noted that the traffic analysis zones grouped data into polygons that too vague to located precise locations of special need populations. Bearing in mind that one TAZ could incorporate up to twelve individual bus stops, specific locations of special need populations needed to known. Consulting the U.S. Census Bureau for more detailed data, demographics were collected on a census block level. Census block data was collected for elderly populations, low income individuals, non-English speaking individuals and physically disabled.

Using the American FactFinder website all demographics for each census block was obtained. The precise distribution of certain demographic information was not available on a census block level and required overall city statistics to be applied. The total population of African American, American Indian, Alaska Native, Asian, Native Hawaiian, Other Pacific Islander, and all other races were multiplied by the percentage of households that do not speak English fluently at home. According to the publication by Shin and Bruno issued by the US Census Bureau in 2003 the percentage of households in downtown Washington, D.C. that speak another language than English is 16.8%. This value also takes into account individuals that feel that they do not have the ability to speak English "very well". To find the number of individuals with physical disabilities for each individual census block manipulations using statistical percentages was performed. The total population of each block was multiplied by the percentage of 8%. The same procedure was applied to find the amount of low income populations. In the case of low income individuals the total population was multiplied by 20.2%. Both of these percentages were based on a state and county data from US Census Bureau (2009).

Latitude and longitude coordinates were found for each census block centroid as well as Metrobus and Metrorail stops in order to calculate inverse distances needed for the benefit function. The benefits for all bus stops were calculated based on the block centroids and population size.

Ten different weighting schemes were evaluated as a sensitivity analysis in order to account for different decision maker inputs (figure 14).

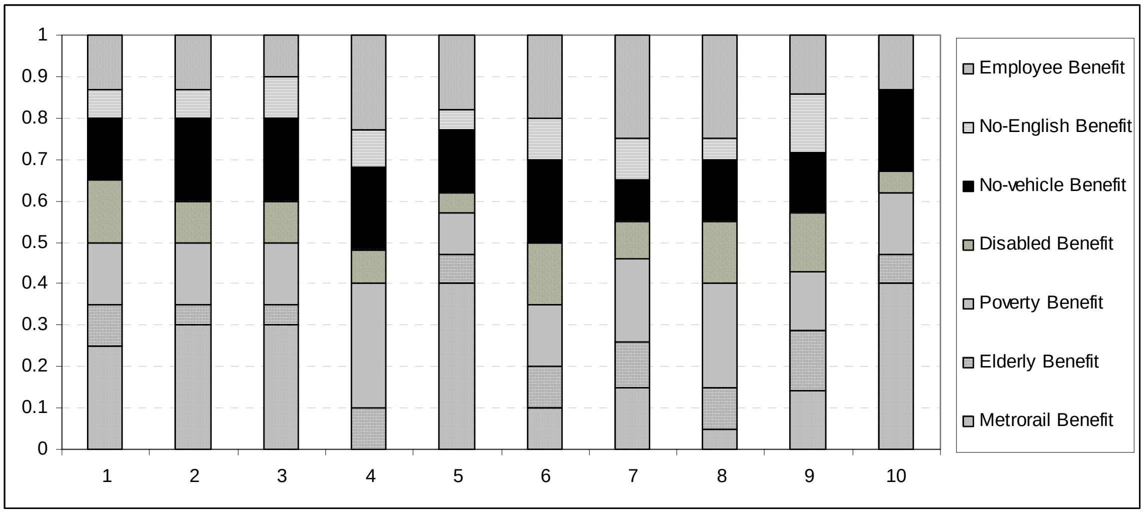

Figure 14 Sensitivity analysis weighting schemes

Once all inverse distances, population sizes and distance factors were known, the benefits for each bus stop were utilized within the optimization formulation. The maximum benefit was calculated for 10 different weighting scenarios, where the maximum number of bus stops was defined as $\eta = 20$, $\eta = 40$, and $\eta = 60$ (figure 15). The optimization formulation was solved using linear programming solver, using the simplex method.

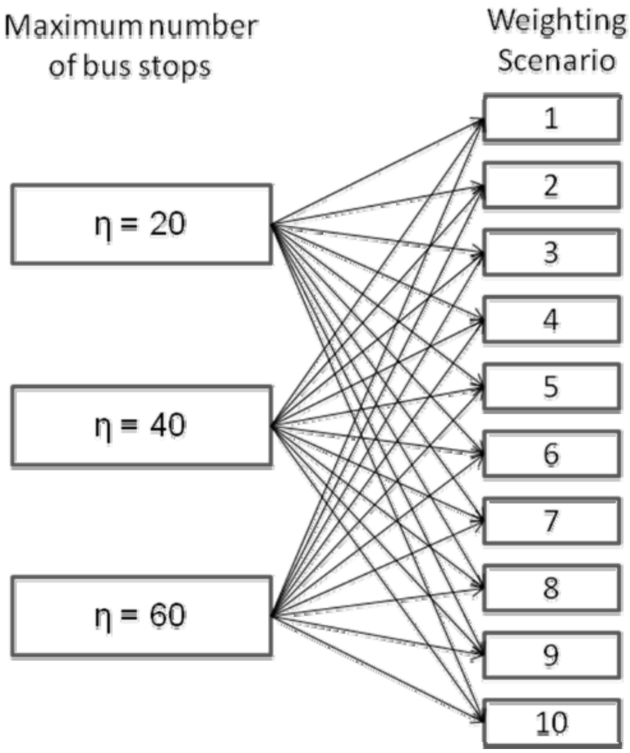

Figure 15 Distribution of optimization model scenarios

The selection of the weighting scheme to be used for the simulation portion of this research was based on probability. The weighting scenario that yielded the greatest count of bus stops within the most frequently chosen stops for all weighting scenarios was selected. It was assumed if a bus stop was habitually chosen despite the different weighting scenario its benefit must satisfy the majority of cases. The ranking of the most chosen bus stops in all three cases can be seen in the tables presented in the appendix.

4.4 Simulation Modeling

The microscopic platform, AIMSUN 6.0 NG, was utilized to simulate a real life evacuation scenario using the optimized bus stop locations. Residual evacuation personal vehicle traffic was generated using the trip generation and distribution models discussed previously. Five separate simulations were evaluated based on the number of optimum evacuation bus stops: 20, 30, 40, 50, and 60. Ten replications are simulated for each number of evacuation bus stops using a new random seed for each replication. An average is then established from all ten replications.

4.4.1 Network Calibration

In order to utilize a simulation network to accurately represent a case study area calibration of the network must be completed. Detectors can be placed throughout the simulation model in order to acquire traffic counts from the virtual traffic demand. These counts can then be compared with field data collected from the case study area. The simulation model can then be modified to match real traffic conditions. The coefficient of determination is used as a performance measure, whereas, values closer to one represent satisfactory calibration. Other performance measures can be used, such as mean square error (MSE) or root mean square error (RMSE) to evaluate the model's ability to simulate real life conditions in regards to observed data. Once the simulation traffic counts become similar to the field traffic counts and a R^2 close to 1 is obtained the network is successfully calibrated.

4.4.2 Simulation Scenarios

All simulation scenarios contain a certain amount of traffic input similarities. The personal vehicle evacuation traffic will be loaded into the network in a four hour time interval. The evacuation traffic is divided into four one hour demands that arrive in the network exponentially. All needed bus trips will be departed during this network loading time interval. Each origin centroid for each TAZ located within the network has established origin-destination routes that incorporate the corridor evacuation routes. Vehicles are assigned to follow origin-destination routes at 100%. A standard network clearance time of three hours is provided to clear grid lock intersections, bottleneck sections, and have the majority of traffic reach safe zones.

Each simulation scenario has to contain a require number of bus trips in order to effectively evacuate all the special need populations within the case study area. For simplicity simulation purposes the required amount of trips was evenly distributed among the available evacuation bus stops. A standard headway interval was implemented in the deployment of evacuation buses. A standard deviation was used in the departure of buses in order to more accurately represent the irregularity of an evacuation situation. Assuming the evacuation bus reaches maximum passenger capacity in one stop each evacuation bus route will only contain one stop. Therefore, one bus trip will only contain one evacuation bus stop of 50 passengers. The bus routes will represent current bus routes used within the case study area until the pickup location. Once the bus is full of passengers the bus will precede to the nearest corridor evacuation exit.

5 RESULTS AND DISCUSSION

The results for the research fall under two main categories: the mathematical model and the simulation model. The simulation model was dependent on the results found from the optimization model. After reviewing the results from the optimization model it was decided to execute the model for a second time with added spatial constraints before simulating the results. The results found in this research proved to be very fascinating and will be presented and discussed in the following chapter.

5.2 Trip Generation and Distribution Results

After applying the Thiessen polygon method the distribution of everyday background was known. The purpose of presenting these results is to verify the robustness of Thiessen polygon method to represent spatial data. Safe zone 4 and 9 produced the most amounts of car trips entering the network from the zones located outside the network area (figure 16). This number differs from the amount of truck vehicle trips entering the network. The safe zone that produces the most truck trips entering the network is safe zone 3 and can be seen in figure 17.

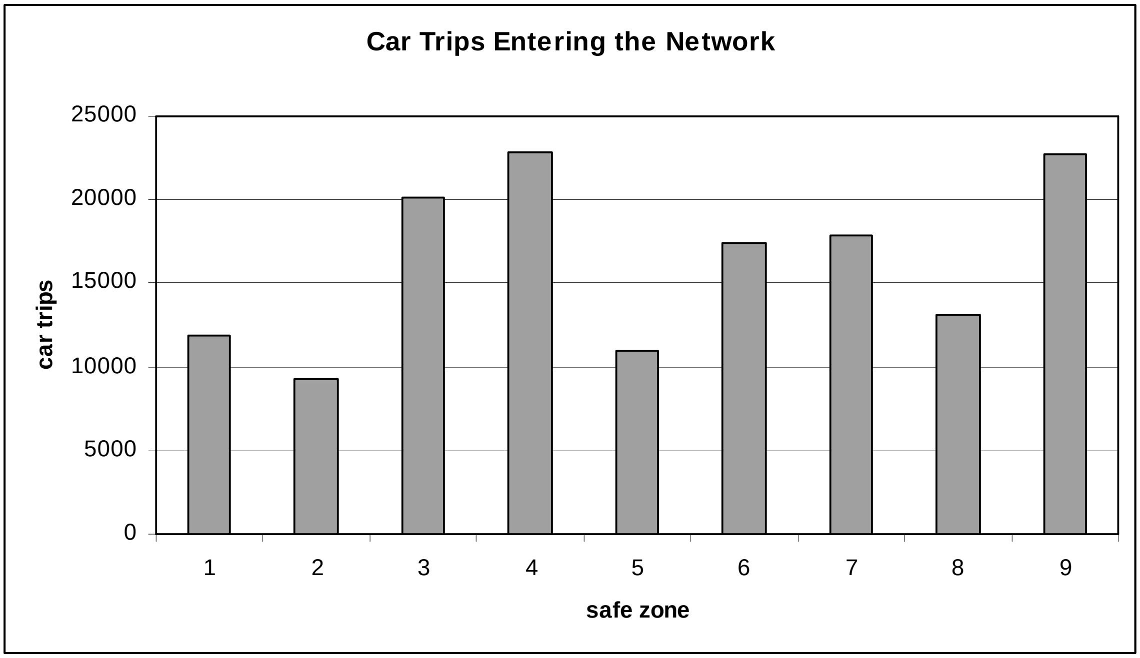

Figure 16 Cars entering the network

The vehicle trips exiting the network were also divided into the 9 safe zones employing the Thiessen polygon method. The vehicle trips exiting the network favored the same safe zone centroids as the entering trips. The distribution of the trips generated inside the network area traveling to the outer zones is represented in the corresponding figures found in the appendix.

The Thiessen polygon method proved to accurately represent the trips entering and exiting the network. It can be seen from the bar graphs that a large amount of vehicle trips are being produced or are attracted to these outer metropolitan TAZ. If these trips were not represented in the simulation network the calibration of the network could have been greatly affected.

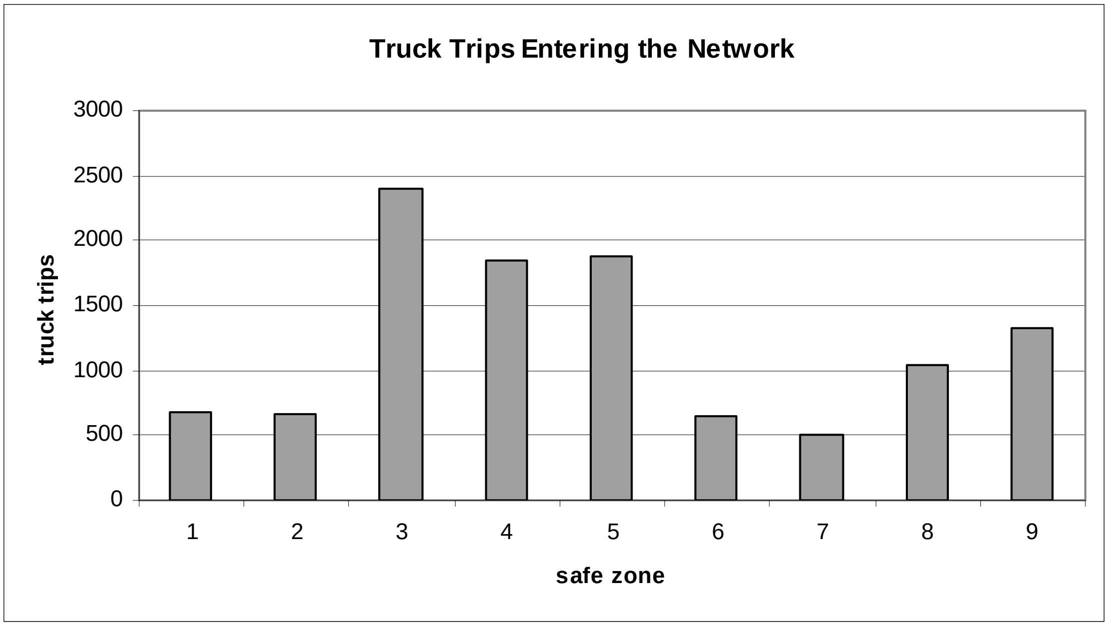

Figure 17 Trucks entering the network

5.2 Mathematical Model Results

The mathematical results yielded total benefit of evacuation bus stops according to the weighting scheme, and maximum number of bus stop occurrence; both of which are dependent upon the decision maker's preferences. To find the results best to simulate for the evacuation scenario several step were taken.

5.2.1 Sensitivity Analysis for Weighting Scheme Selection

It was noted that the there is some relationship between the individuals found in the categories chosen for the mathematical model. Persons who choose not to own a vehicle could have been influenced by a low income. Elderly and physically disabled persons might find it difficult to work and result in falling into the category of poor as well. Considering this relationship an individual might be accounted for twice in the given optimization formulation for special need populations. Therefore, a weighting scheme had to be developed in order to carefully account for all special need populations without over emphasizing one group or another.

Finding a correlation between the categories was not possible due to the fact that some of the data for certain categories was based off of percentages of total population resulting on an inaccurate correlation very close to one. A sensitivity analysis was performed in order to find the most representative weighting scheme for the give case study area. The optimization model was executed 10 times for each maximum number of bus stop occurrences (η). For each weighting scheme, the frequency that the η best ranked bus stops occurs for all weighing schemes and for all η maximum number of bus stops scenarios was graphed (figure 18). The scenario that most frequently selected the same bus stop locations for all 10 scenarios was then chosen for simulation purposes.

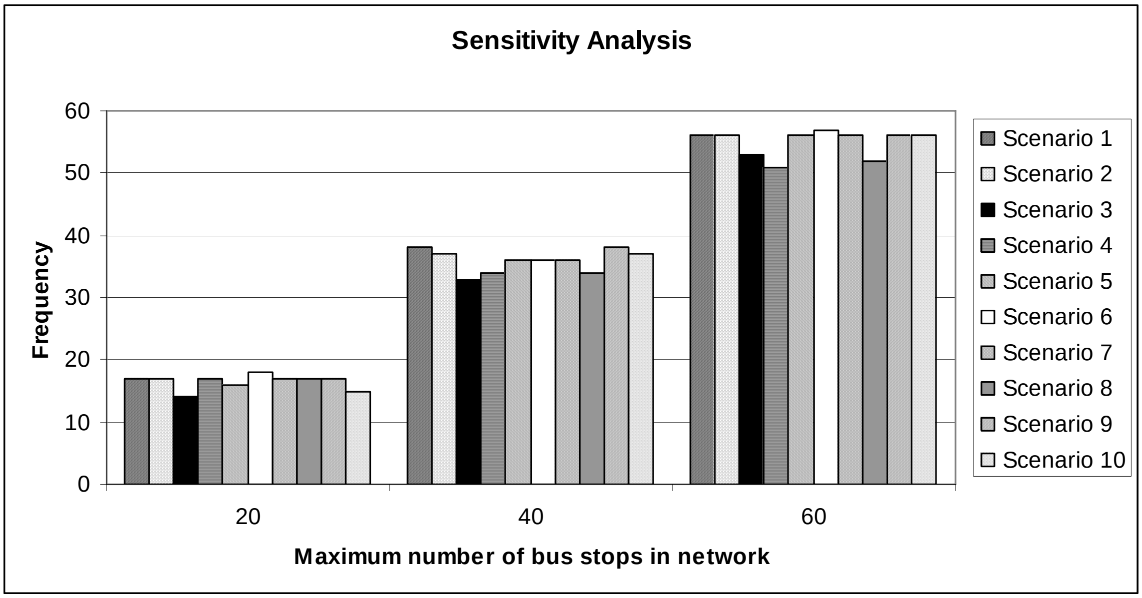

Figure 18 Sensitivity analysis

In figure 18 it can be seen that that the bus stop location frequency between all 10 weighting scenarios are very close, however, in general weighting scheme 6 had the most frequent selected bus stop locations ranked amongst the best ranked for all 3 maximum number of bus stop scenarios. The frequency of selected bus stops is better represented in table 2. The largest frequency of same bus stop locations is highlighted for each bus stop scenario. Weighting scheme 6 contained the two of the three highest location selection frequencies. The bus stop scenario 40 did not have the largest frequency of selected bus stops for weighting scheme 6 as the other 2 scenarios, but the frequency for the 40 bus stop scenario for weighting scheme 6 was amongst one of the highest frequencies. It was assumed that if a location was chosen most frequently for all weighting schemes its location must be optimal for all special need populations.

Table 2 Bus stop frequency organized by bus stop scenario

scenario	**Weighting Schemes**									
	1	2	3	4	5	6	7	8	9	10
20	17	17	14	17	16	18	17	17	17	15
40	38	37	33	34	36	36	36	34	38	37
60	56	56	53	51	56	57	56	52	56	56

The weights adopted for weighting scheme 6 are shown in table 3. This scheme produced the best weights for bus stop locations in the application of this case study because of the weights being distributed evenly between all the special need population categories.

Table 3: Weighting scenario 6

Category	Metrorail	Elderly	Poverty	Disabled	No-vehicle	Non-English	Employee
Weight	0.1	0.1	0.15	0.15	0.2	0.1	0.2

5.2.2. Bus Stop Clustering

The bus stop locations yielding from the optimization model proved to have the highest benefit for special need populations in downtown Washington, D.C. core area. The benefit for all three different conditions of number of maximum bus stops can be seen in table 4. As expected the total benefit increased as the total number of maximum optimum bus stops increased. The bus stops chosen in the condition of 20 maximum stops were also selected for the 40 optimum bus stops. Moreover, the 40 optimum bus stops were also chosen in the condition of 60 maximum evacuation bus stops, that is, each condition always included the optimum bus stops selected in the preceding condition.

Table 4: Maximum benefit of trial 1

η	total benefit
20 bus stops	42.88
40 bus stops	68.30
60 bus stops	79.32

Based on the spatial distribution of the 20 optimum bus stops resulting from the optimization model several inferences can be made. Figure 19 indicates that the model delivered the 3 necessary bus stops surrounding the terrorist interest point, Chinatown Gallery Place Metro Station, as a constraint was declared for that specific TAZ zone enforcing a minimum of 3 bus stops. These 3 bus stops were declared to be located within this TAZ because this is where the terrorist threat is located. It can also be seen that the majority of the bus stops are clustered in one region of the network. This clustering could be due the large amount of employees located in this region.

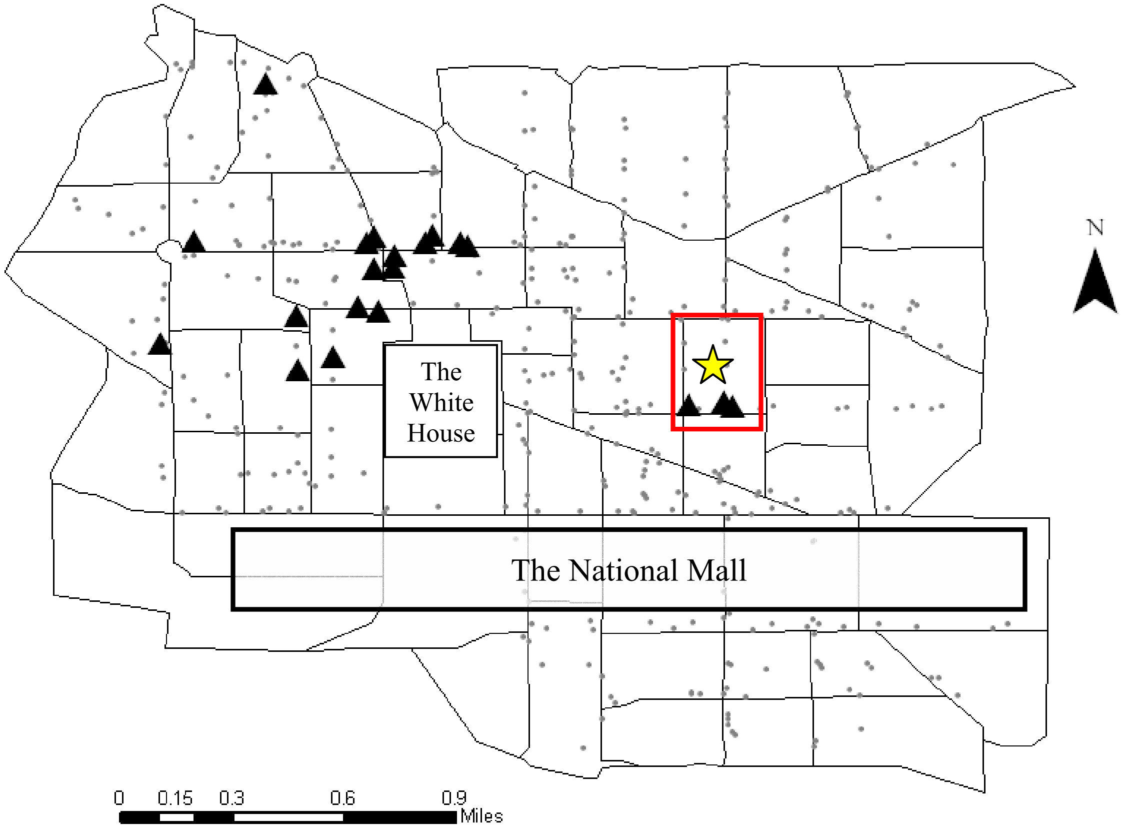

Figure 19 Optimum 20 bus stops from trial 1

The total benefit found for the 20 bus stop locations represented in table 3 was 42.88 and was one of the highest among all 10 of the weighting scenarios for the 20 maximum bus stops scenario. Even though this scenario produced one of the highest benefits, the location of bus stops is not ideal for planning purposes, because the majority of selected stops are all located North West of the White House. This clustering of bus stops results in the majority of the downtown area not containing any evacuation bus stops. The low number of evacuation bus stops with the addition of clustering results in only a few TAZ containing evacuation stops, leaving most of the zones empty without any evacuation bus stops.

When the maximum number of bus stops was increased to the 40 bus stop locations, the benefit of the bus stops also increased to the amount of 68.3. This is a likely result in that the more bus stops selected the more benefits the objective function will contain to sum (figure 20).

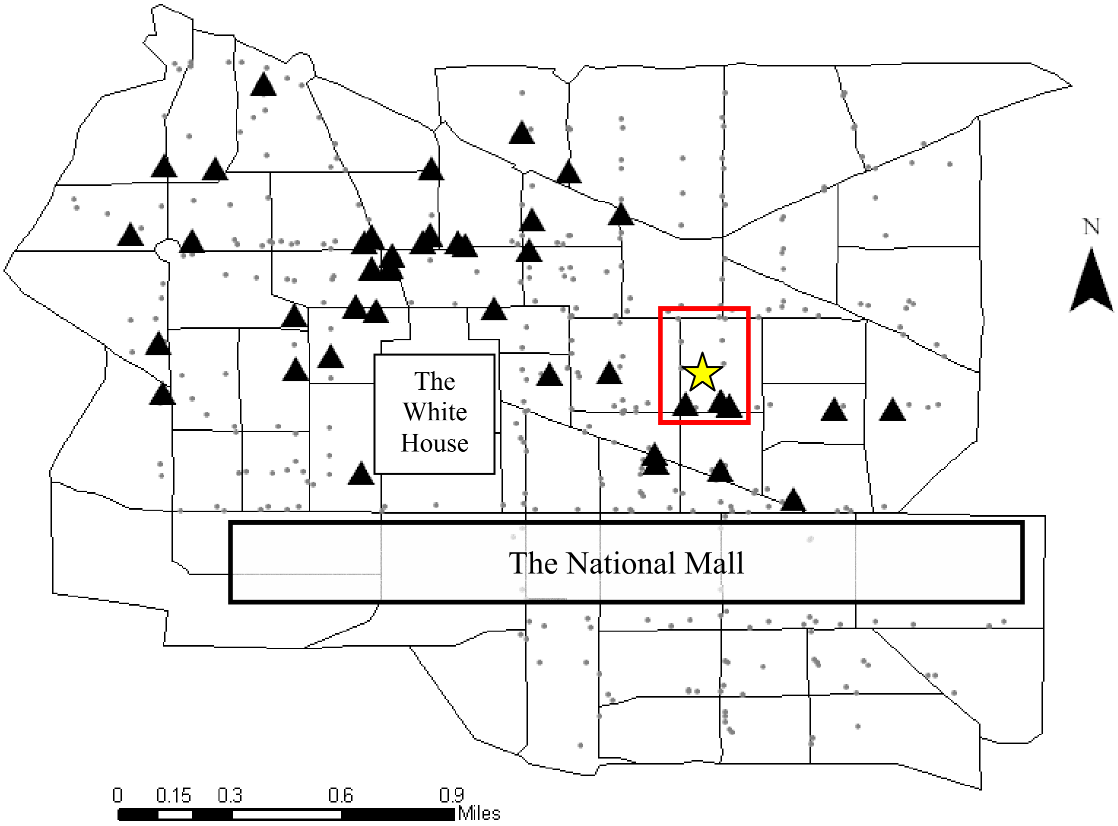

Figure 20 Optimum 40 bus stops from trial 1

The 40 optimum bus stop locations seem to have an improved spatial spread throughout the downtown area. When examined closely one can see a lack of evacuation bus stops in the lower third portion of the region, as well as the north east corner. The lower portion of the case study area incorporates the National Mall and attracts many tourists daily. Therefore, it is vital that an evacuation bus stop is located in this area and extra constants are added to the formulation to account for this area.

After adding another 20 bus stops for a total maximum number of 60 bus stops, the maximum total benefit increased to 79.32. Figure 21 illustrates that the spatial distribution of the 60 bus stops is consistent throughout the case study area. By allowing the model to choose 60 bus stop locations, the greatest benefit was achieved and the overall spatial distribution was greatly improved.

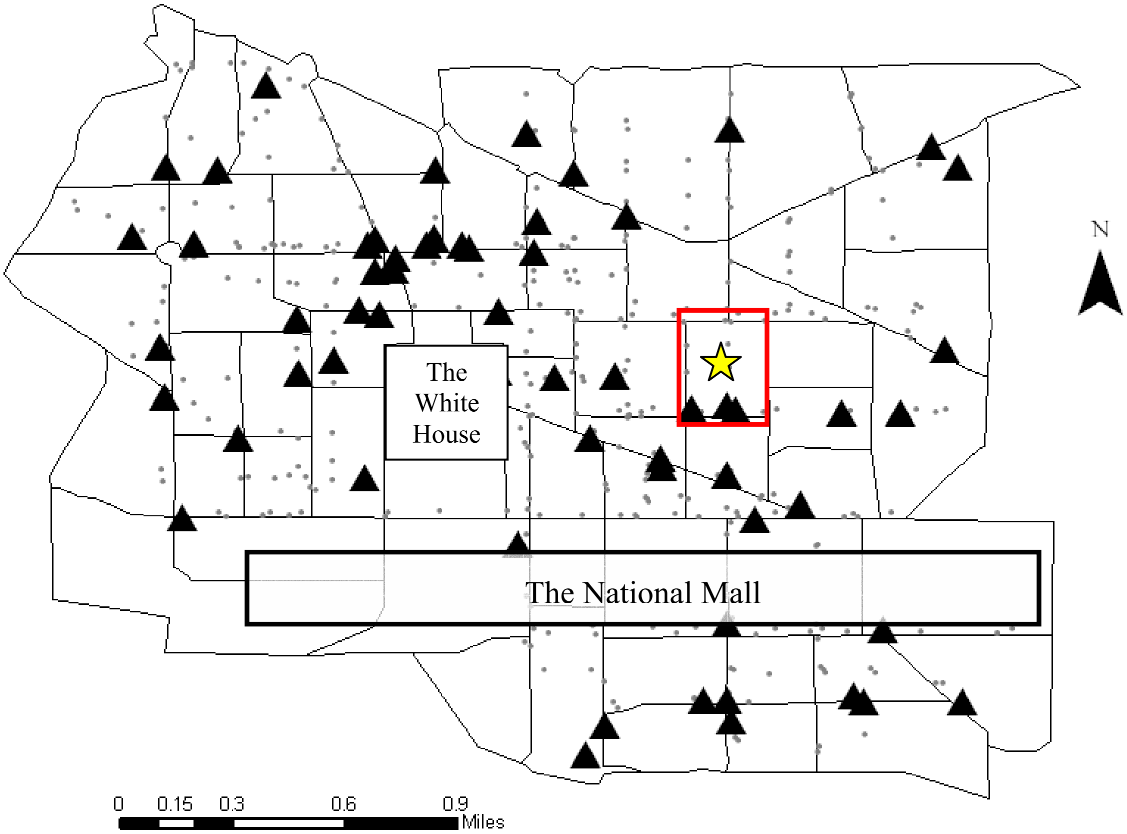

Figure 21 Optimum 60 bus stops from trial 1

After reviewing the results of the mathematical formulation the model was implemented for a second time in order to reach results that would be more practical for actual planning purposes even if a lesser number of maximum bus stops than 60 are required. The first set of bus stop location results did yield the stops with optimum benefit for special need populations but did not take into account travel time of the evacuee to reach the bus stop. If resources would only be available for 20 or 40 maximum evacuation bus stops the optimization model will need to introduce additional constraints.

In an actual evacuation bus stop locations must be available for service throughout the entire network and not just one concentrated area. Despite that this concentrated area is the area that resulted in the largest benefit it is understood that the bus stops should be more spatially distributed in order to service all special need populations throughout the entire downtown area to comply with practical evacuation planning.

5.2.3 Addition of Spatial Constraints

In order to obtain the number of evacuation bus stops that are more evenly spread throughout the case study area a grouping of TAZ was executed. As stated previously in the methodology, the complex formulation model easily allows for the decision maker to apply extra constraints as needed for the study area. Figure 22 illustrates the 3 x 3 grid implemented for this in order to prevent the clustering effect. Once the TAZ were grouped by the 9 grid sections 9 new constraints were inserted into the formulation model.

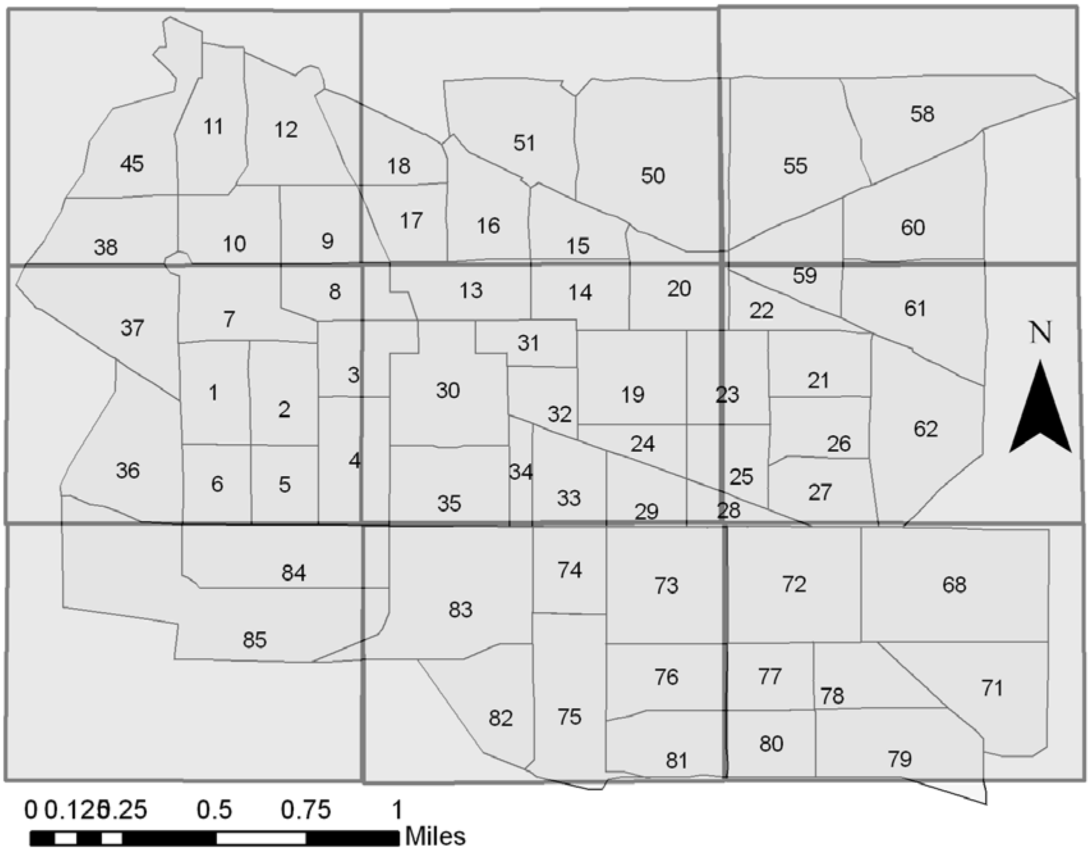

Figure 22 Grid grouping of TAZ

$$\sum_{g=1}^{G}\phi_{b,g} \geq \varepsilon_g \tag{24}$$

Where,

g = the group of TAZ that fall into a grid cell

ε_g = Minimum number of bus stops in each TAZ group g;

The new total benefits for each maximum number of bus stops scenario was obtained by executing the optimization model. In this new trial of the model runs were completed for 20, 30, 40, 50, and 60 maximum bus stops. The total benefits can be seen in table 5. The weighting scheme that used to calculate the total benefit was weighting scheme 1. It was the weighting scheme that represented the most frequently chosen bus stops.

Table 5: Grid implementation total bus stop benefits

η	total benefit
20	27.64
30	39.67
40	48.98
50	55.50
60	58.51

Assuming the same methodology for the selection of the most representative weighting scheme based on the sensitivity analysis, after the implementation of the grid and equation 24, figure 20 displays the new locations for the 20 optimum evacuation bus stops.

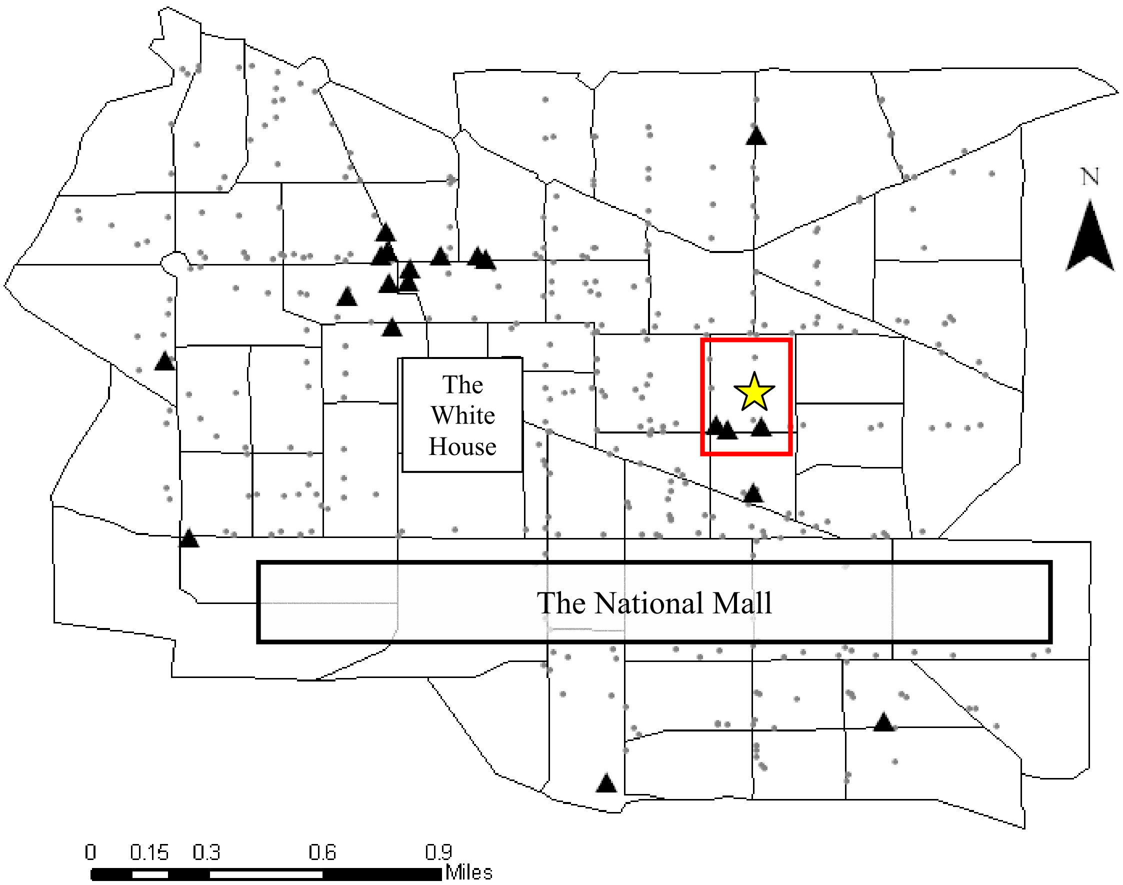

Figure 23 Optimum 20 bus stops after grid implementation

This is an improvement from the first trial run of the optimization model. The bus stop locations now selected have only about half the amount of bus stops clustered in the region located north west of the White House. The three most important bus stops are still located next to the terrorist threat area, as the previously mentioned constraint is still held. Three new locations of bus stops are now found in the lower portion of the area catering to tourists who are visiting the National Mall, and one evacuation stop is now able to service the north east corner of the case study area.

Unlike the first trial of the optimization formulation a scenario of 30 maximum bus stops was modeled. The distribution of the 30 optimum bus stop locations is represented in figure 24. This scenario contains all the same bus stop locations as the 20 bus stop scenario but has an additional 10 locations. The new grid equations add to the formulation allow for the 10 new locations to be more evenly distributed throughout the case study area. There is still a large amount of stops located to the North West of the White House but several other locations are now represented. By allowing the model to select 30 bus stops the service area of evacuation bus stops has expended but certain regions (i.e. the eastern portion of the case study area) are still lacking evacuation bus stops.

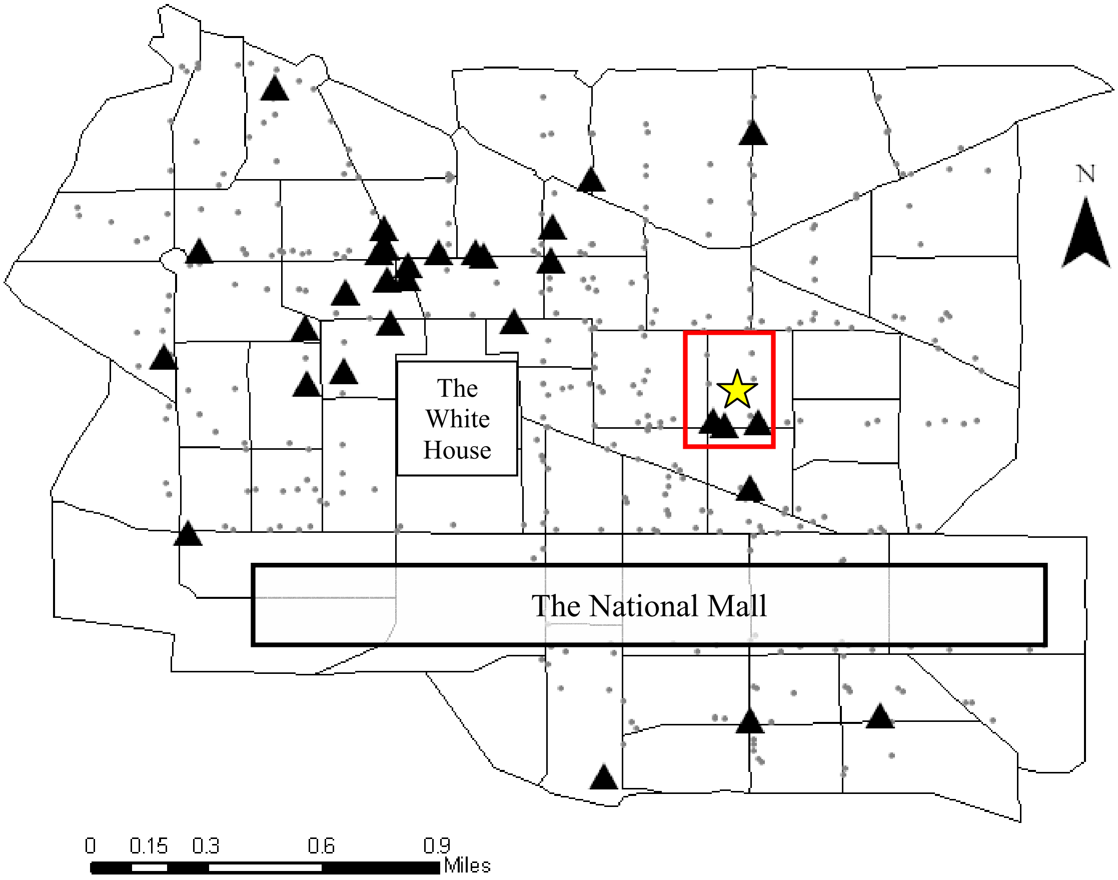

Figure 24 Optimum 30 bus stop locations

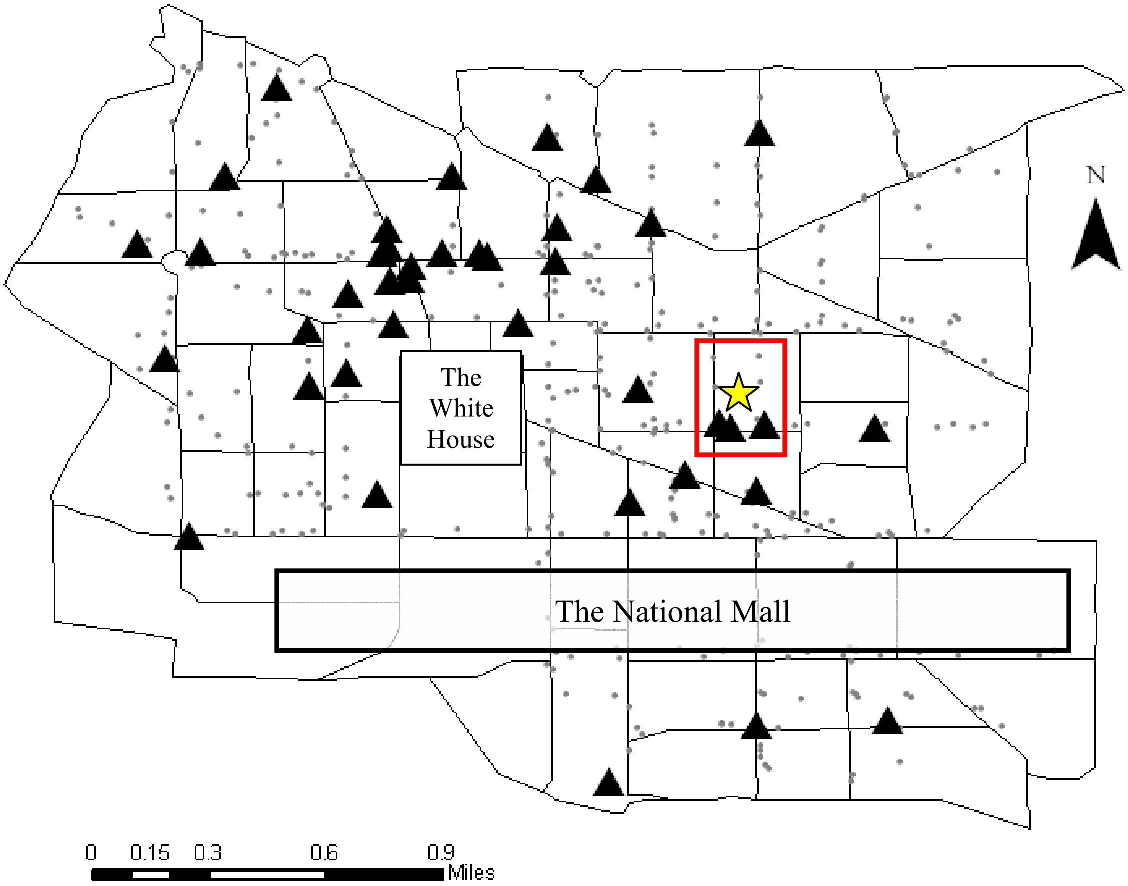

Figure 25 Optimum 40 bus stops after grid implementation

Figure 25 depicts the major improvement of the addition of the new constraints to the optimization model. In the first trial of the optimization model the 40 bus stop incident, the lower third portion of the case study area was still lacking evacuation bus stops. The results from the grid implementation optimization model resulted in bus stop locations that are now more favorable for actual evacuation planning by having an improved spatial distribution. The lower third portion of the case study area now incorporates 4 evacuation bus stops. These bus stops are crucial for evacuation purposes because of the large amounts of tourists located in this region visiting the National Mall.

The locations of the 50 optimum bus stops include the improved 40 locations plus an additional 10 new locations (figure 26). Note worthy new locations include 3 bus stop locations in the north eastern portion of the case study area. In the previous maximum bus stop scenarios this area has not contained any evacuation bus stops. The 50 locations represent the case study well spatially and provide evacuation service to special need populations in all the regions. The benefit function did not include tourist as one of the special need categories but evacuation bus stop locations are starting to be selected along the perimeter of the National Mall as the maximum number of stops is increased.

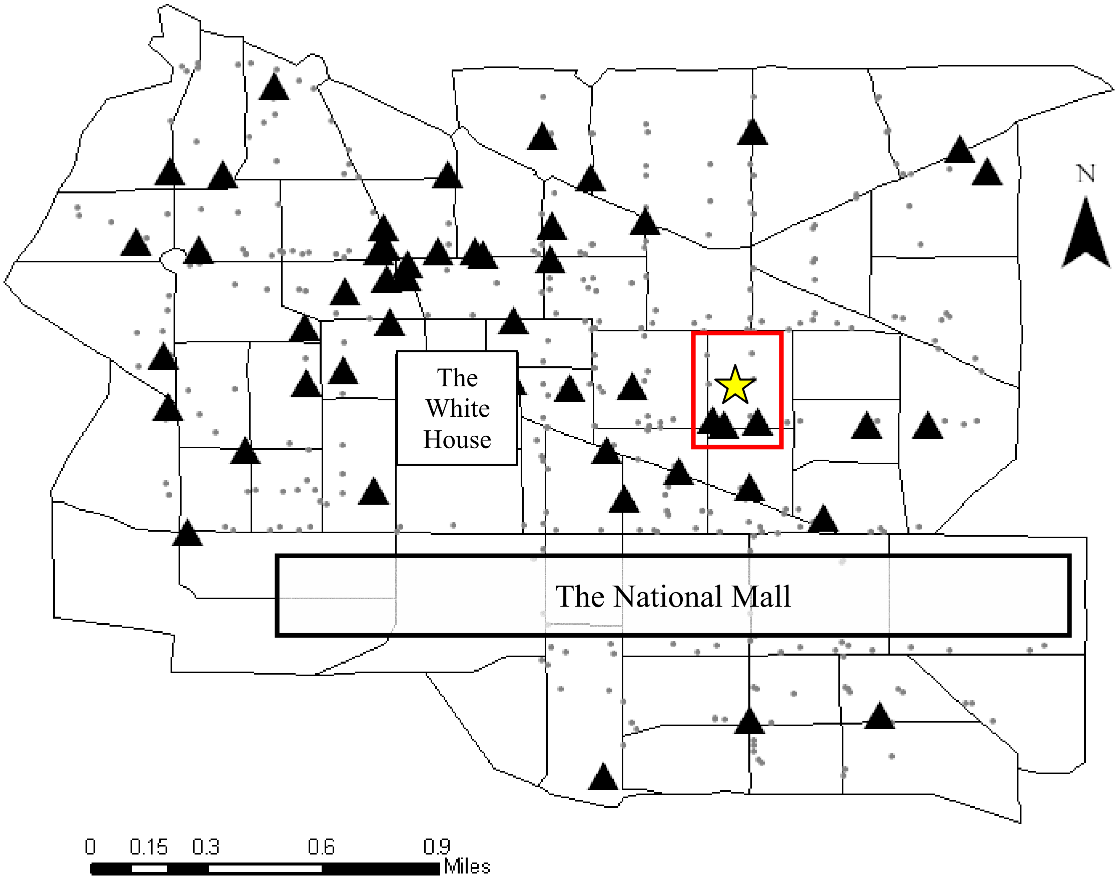

Figure 26 Optimum 50 bus stop locations

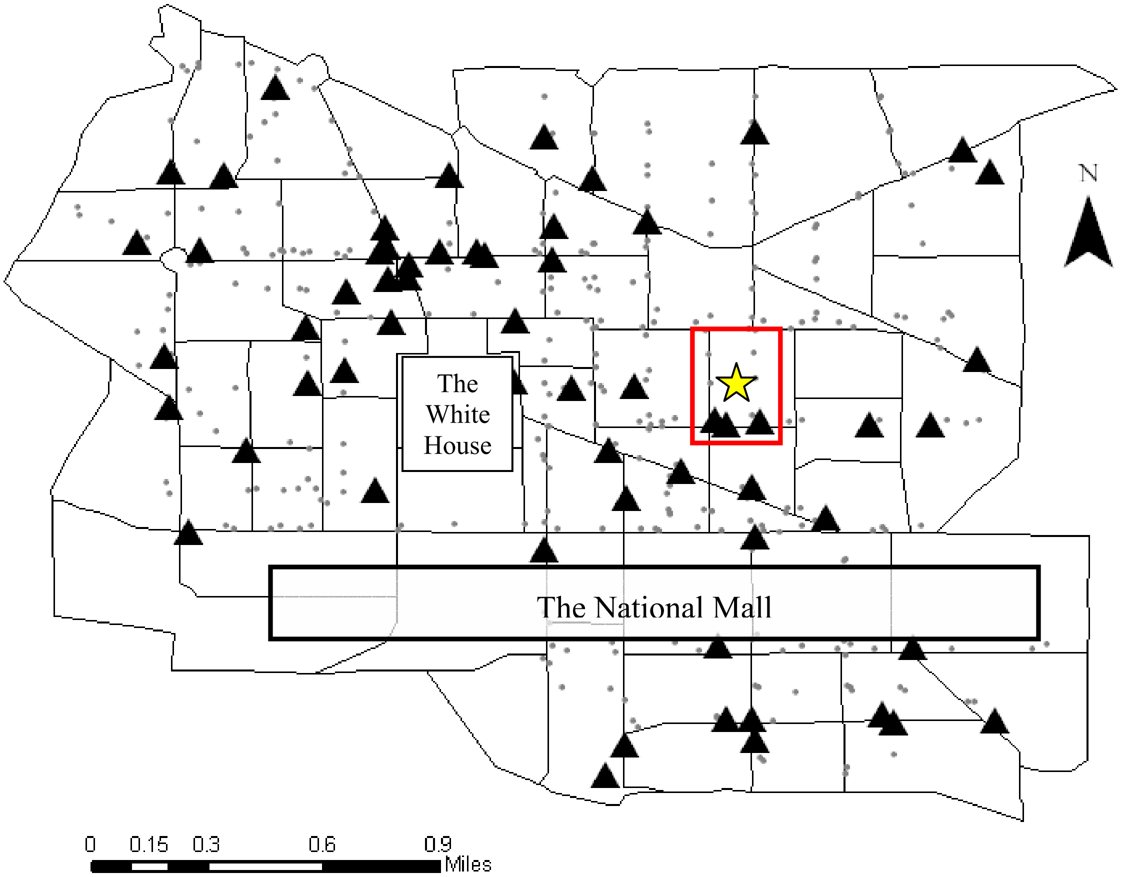

Figure 27 Optimum 60 bus stops after grid implementation

The locations picked for this scenario contained all the locations selected in the 20, 30, 40, and 50 maximum bus stop locations. The grid implementation for the 60 bus stop incident did not result in much improvement from trial 1. In trial 1 the spatial distribution of evacuation bus stops was constant for the area taking into account that the model had 60 bus stop locations available to select. The results from both optimization models proved to be very similar which can be seen by comparing figure 27 to figure 21. If the optimization model has the ability to select more optimum locations, more traffic analysis zones will contain an evacuation stop giving a more wide spread service area of bus stops.

5.3 Network Calibration

Calibration for large microscopic networks requires large amounts of time. For this research only certain intersections were used for the calibration process. Actual field traffic counts were provided by DDOT in the signal timing Synchro files. The counts were known to be for off hour and were provided for a one hour interval but the exact time of the counts was unknown. The time used for calibration was 10 am for a weekday. This time was chosen because it is the time that the background traffic will begin to load the network before the evacuation commences. During the calibration different route choice modes were evaluates to most accurately represent the traffic of downtown Washington, D.C. The route choice models provided through AIMSUN include; fixed shortest path during free flow conditions, Binomial, Proportional, Logic, C-logic, and user defined route choice model. Other default parameters were altered and evaluated in appropriation to simulate real life traffic conditions within the microscopic platform. A final result of an R^2 value of was obtained through the calibration process (figure 28). Default parameters such as car following, stopping, and lane changing behavior had to be modified in order to reach this result.

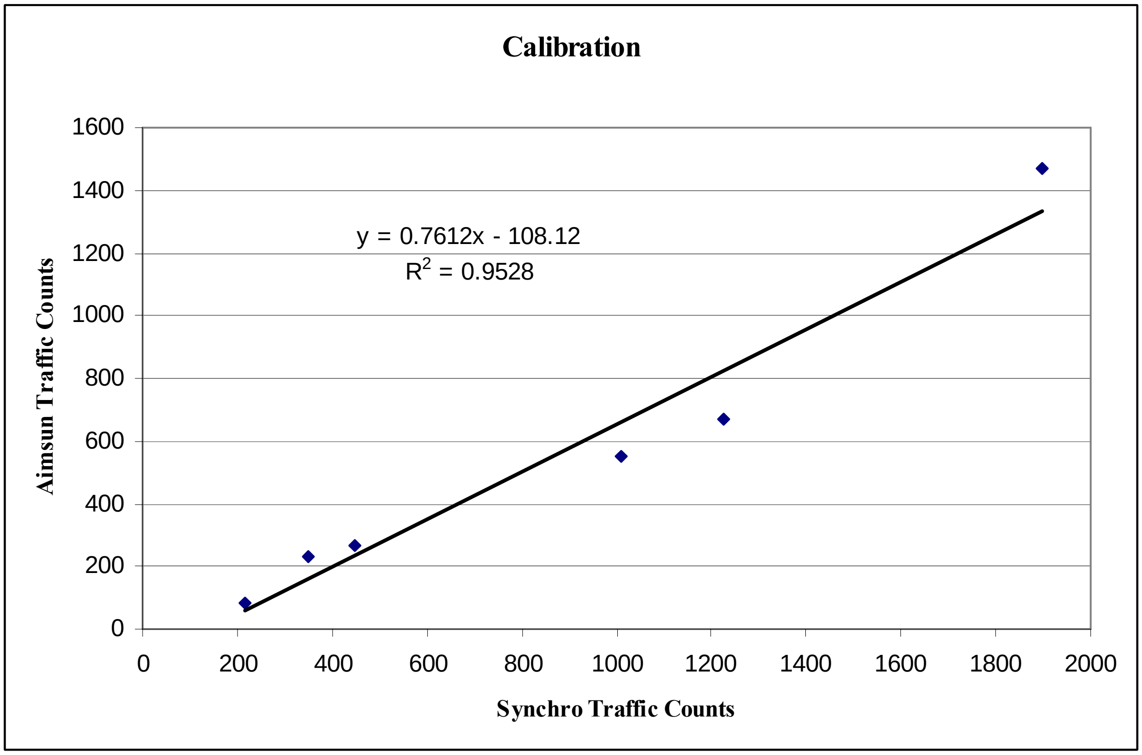

Figure 28 Final calibration results

The calibration process compared the traffic counts of six separate intersections. The intersections were chosen based on their location and importance for the evacuation scenario. It was essential that intersections and roadways used as the corridor evacuation routes represent real life traffic conditions. The intersections that were chosen for the calibration process include: L St & 19th St, Rhode Island Ave. & 17th St, Constitution Ave & 12th St, Pennsylvania Ave. & 20th St, New York Ave. & 6th, and 9th St & D St. The traffic counts were compared at each intersection based on direction of traffic: eastbound, westbound, northbound, and southbound. This narrow calibration was limited due to a restriction of field data for the case study area. Although some traffic count data was obtained the actual time of the counts was unknown. This effects the calibration of the model because the model is being calibrated using origin-destination matrices for a particular time of day. The pattern of traffic demand behavior normally follows the graph in figure 29. By not attaining exact field traffic counts an accurate calibration is difficult to conduct.

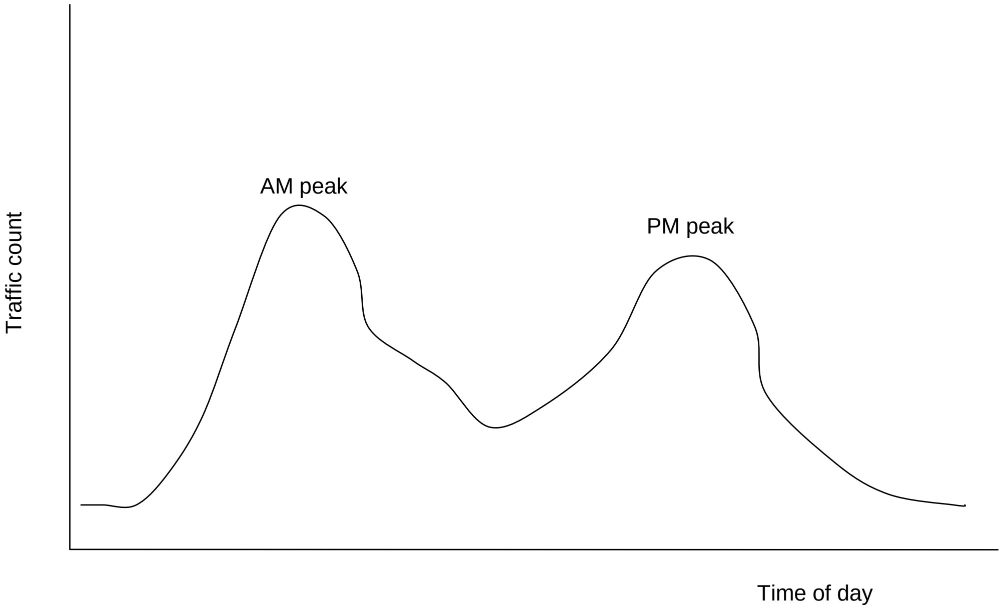

Figure 29 Traffic demand peak periods

5.4 Simulation Results

The simulation results for this research are presented using specific measures of effectiveness: delay time (sec/mi), travel time (sec/mi), and stop time (sec/mi). All results presented are for buses only (the main objective of this research is focused on evacuation of public transit vehicles). The average results found from each replication are presented in this chapter. The individual replication results can be found in the appendix.

The definition for each measure of effectiveness is defined as follows by the AIMSUN's user manual. Delay time is the average delay time experienced by the vehicle. It is the difference between the actual travel time recorded in the simulation replication and expected travel time calculated at the beginning of the simulation. Travel time is defined as the mean travel time for all the public transit vehicles to complete their defined public transit line. This is the mean time of travel for each public transit vehicle from time of entrance until exiting the network. (This measure of effectiveness was chosen despite some public transit lines consisting of more travel distance than other public lines.) Lastly, stop time is defined as the average amount spent at a stop per vehicle. This stop time includes the time spent at bus stops as well as stops experienced by the vehicle at red lights, bottlenecks, and grid locked intersections.

A standard dwell time was calculated and applied to all evacuation bus stops. Using standards set by the Highway Capacity Manuel a dwell time of 297.5 sec was calculated. This time includes door opening and closing, boarding time for each passenger, and wheelchair loading. Every WMATA bus is either equipped with a low floor ramp or hydraulic lift. The wheel chair boarding time for a low floor ramp ranges from 60 -120 seconds; the dwell time for hydraulic lifts range from 120-200 seconds. Taking into account both type of wheelchair loadings a standard deviation of 60 seconds was applied to the dwell time.

Results were recorded for 5 different replications for the 5 different maximum number of evacuation bus stop location scenarios. One replication would take on average 4 hours to simulate using the batch function of AIMSUN. If the replication was simulated using the animation function the simulation time was extended to 6 hours. The replications provided results that were moderately consistent with a small variation with each seed replicated. All results found for each replication were than averaged to analyze any trends within the results of the different scenarios.

The different delay times for each bus stop scenario are shown in figure 30. By routing the evacuation buses to the nearest evacuation corridor it was attempted to maintain delay time to a minimum. The largest delay time was experienced by the 40 bus stop scenario. The buses in the 20 bus stop scenario could be experiencing a high delay time because the congestion of all the buses servicing the same small amount of stops. The buses in this scenario had to be set a very close headway (approximately 2 min) in order to reach the required amount of bus trips to evacuate the case study area. Due to the minimum headway interval and large dwell time, buses servicing the same stop formed larger queues than the other scenarios. The lowest delay time was experienced by the 60 bus stop scenario.

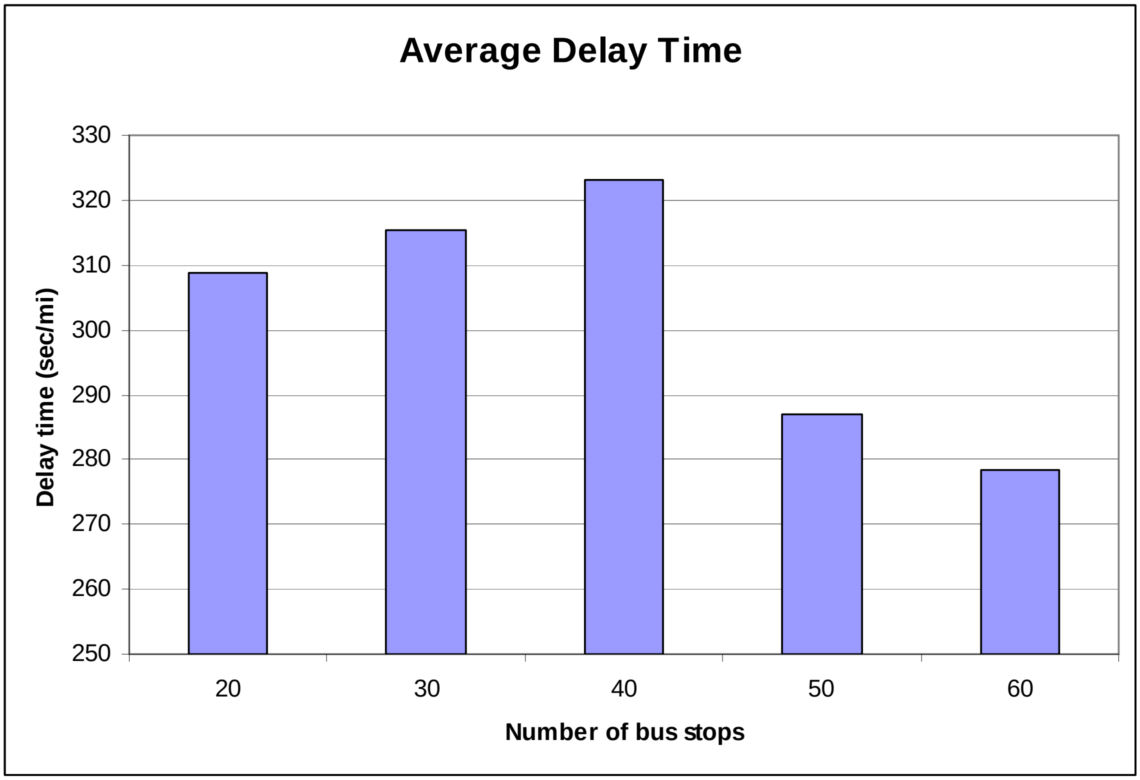

Figure 30 Delay time

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The travel time for each individual evacuation bus is dependent on the route of the evacuation bus. Several bus routes extend through the entire case study area, while others travel just along the perimeter. The routing strategy implemented in this research tried to reduce travel time by exiting all evacuation buses to the nearest evacuation corridor after servicing its assigned stop. Travel time is also dependent in which roadways the bus route service and the level of service. In this research it was decided to find the average travel time of all the evacuation bus routes servicing the entire case study area.

The results found for travel time are consistent with the results obtained for delay time (figure 31). This is due to delay time having a linear relationship with travel time experienced by the evacuation bus. If a bus experiences a larger delay time the travel time will also increase. The average travel time for all the evacuation buses increased until reaching the 40 bus stop scenario. Again, the 40 maximum bus stop scenario had the highest result compared to other replications. On average the travel time was lower for bus stop scenarios that contained more than 40 evacuation bus stops (i.e. the 50 and 60 bus stop scenario). The lowest average travel time resulted from the 60 bus stop scenario. The ranges for average travel time for all 5 scenarios were all within 50 sec/mi. This might seem as a minor difference, but when dealing with evacuation, time is of the essence.

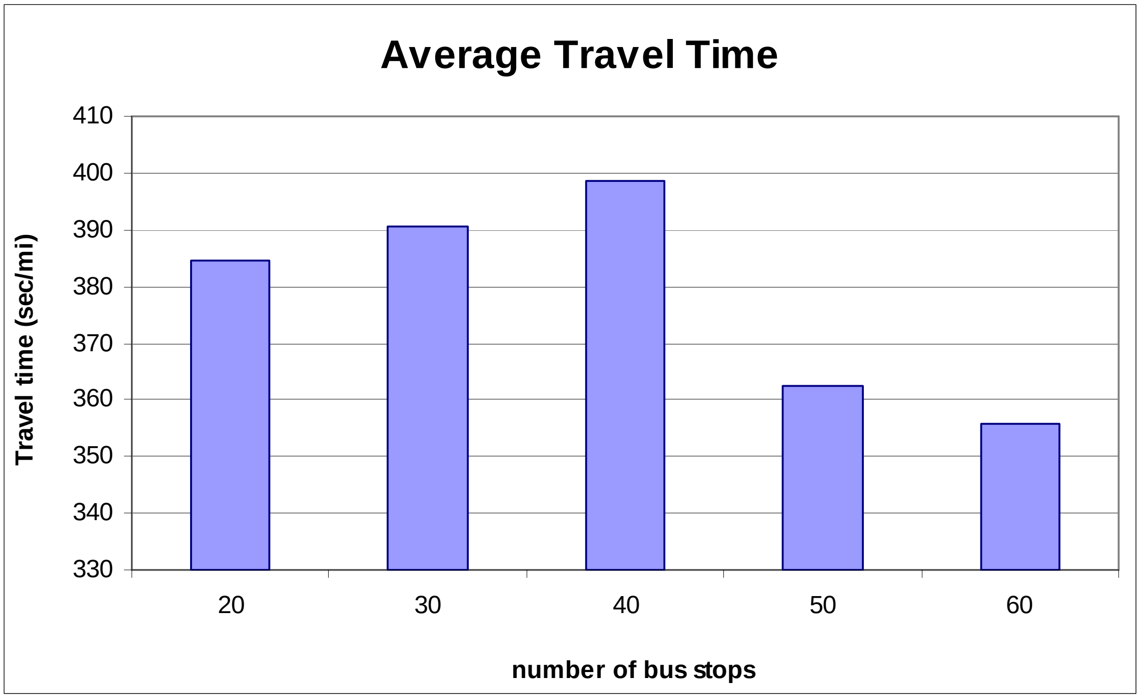

Figure 31 Travel time

The stop times found for each replication bus stop scenario also followed the same patterned of the two previous sets of results. The average stop time for all the replications used for this research can be seen in figure 32. Replications for the 40 bus stop scenario had the largest stop time when compared to the stop times for the other scenarios. The 60 bus stop scenario had stop times that are that were the lowest of all the scenarios.

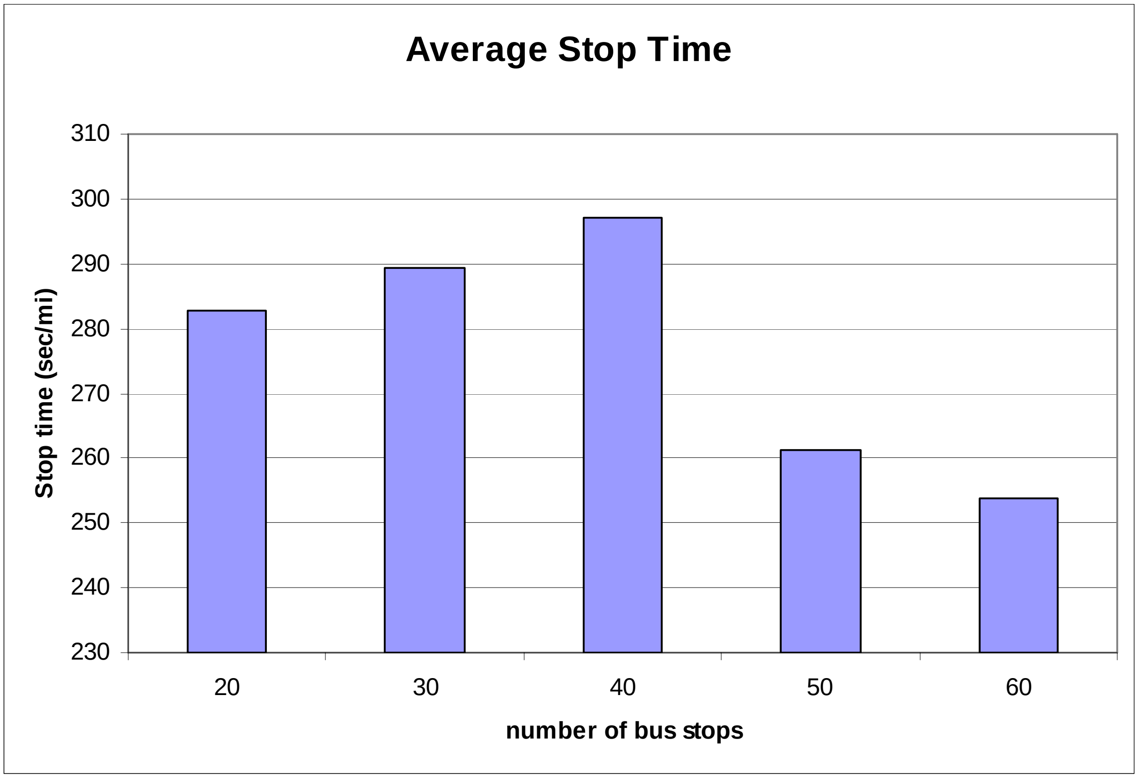

Figure 32 Stop time

Beginning the simulation scenarios with 20 evacuation bus stops and increasing the number of stops by 10 for each succeeding simulation worst scenario was found. The 40 bus stop scenario yielded the highest delay, travel, and stop time and should not be implemented for evacuation. This could be due to the bus stop locations still requiring a large amount of evacuation trips. It can be seen once the simulation is set for the 50 bus stop scenario and the number of required trips per bus stop decrease from 50 to 40 reducing the delay, travel, and stop time. Also, the bus routes required for this scenario might require longer evacuation travel distances.

After reviewing all the results for each measure of effectiveness, it can be seen that the 60 bus stop scenario produced the most efficient evacuation time. The delay, travel, and stop time were all the lowest when compared to the other simulated scenarios. This is due to the less required buses per evacuation stop causing queues at evacuation stops for waiting evacuees. Furthermore, the stops were more evenly spatially distributed in this scenario allowing for evacuation buses to slow evacuating traffic equally in the case study area and not just in concentrated sections. More bus stop locations are located along the boarder of the case study area allowing for shorter bus evacuation routes.

6 CONCLUSION

In conclusion, this research effectively addressed the optimal allocation of bus stops for the purpose of evacuating special need populations. The proposed methodology is applied on a real life case study to evaluate the effects of the location, number, and distribution of optimal evacuation bus stops. A microscopic traffic simulation model is developed to represent the downtown Washington, D.C. area in an evacuation scenario. Input data, such as geometric design, signal timing, traffic demand, and demographics, was used to construct the simulation model.

A linear programming mathematical model using binary variables was developed to select the most suitable location and number of bus stops catering to special need populations in the network. A benefit function aggregates the attributes associated with each existing bus stop based on spatially distributed demographic information. The formulation incorporates the preferences of the decision makers by associating weights to each specific special need group. Furthermore, the flexibility of the formulation allows the decision maker to address specific concerns of the evacuation area.

The use of a linear programming technique for the mathematical model presented in this research yielded satisfactory results. The computational time requirements to achieve the optimal solution were minimal, approximately 3 seconds. For comparison purposes, the same formulation was optimized utilizing a Genetic Algorithms solver, requiring a considerable computational time for the convergence to the same optimal solution. It was then decided that a linear programming approach was the best for this research.

Constraints that compose the optimization formulation can be used to limit the number of bus stops per traffic analysis zone. The application of these constraints avoids clustering of bus stops and produces more distributed bus stop locations within the case study area. Further grouping of TAZ zones through a spatially aggregation process and specifying minimum number of bus stops per TAZ group can aid in overcoming clustering of optimum bus stop locations and provide a more evenly dispersion of bus stop location.

Simulating the optimum bus stop locations with the simulation model that was constructed for this research, evacuation performance results were obtained. As expected the 20 bus stop scenario produced very poor results and did not perform well under the evacuation scenario. The 60 bus stop scenario created a very even spatial spread of evacuation bus stops throughout the case study area. It was assumed that this scenario would have a large travel, delay, and stop time because of the diverse spread of resources and addition of extra bus routes. The results proved the opposite by showing satisfactory outcomes. The simulations for the 40 bus stop scenario produced the highest results for all 5 replications. The 40 bus stop scenario would not be ideal to implement for evacuation purposes for this case study. Each bus stop scenario that contained a greater amount of bus stop locations performed superior. If the case study has the resources to provide 60 evacuation bus stop locations this scenario would be best for planning purposes. This scenario had the lowest delay, travel, and stop time with the best spatial spread of evacuation bus stops.

6.1 Contributions of this Research

The contribution of this research can be implemented to decrease causalities in evacuation scenarios. The importance of evacuation planning for special need populations has become evident in the United States after such catastrophes such as Hurricane Katrina. In the past the majority of evacuation planning is only completed for personal vehicles leaving behind an entire demographic population of persons who do not own vehicles. This research proposes a formulation to prevent such tragic events by giving urban areas the ability to plan properly for evacuations.

The main contribution of this research was the development of a benefit function based on demographic information to find optimum locations for evacuation bus stops that accommodate special need populations. Moreover, the formulation is flexible to incorporate the preferences of different decision makers and specificities of different application areas.

The simulation model constructed for this research is also a major contribution. The network built for this research is very large compared to common microscopic networks built. The network of downtown Washington, D.C. uses current input information data that is utilized by planners aggregated into a microscopic network that can represent individual driver behavior and service characteristics of specific road segments. The simulation model was employed to provide insights on the optimal location and effects of bus stop density on the evacuation performance. The WMATA agency had asked that certain constraints and scenarios be evaluated for public transit use in an evacuation scenario and that has been completed in this research.

6.2 Limitations

When performing this research several limitations were noted. Very fine demographic data is required to properly represent the special needs population when calculating the benefit of bus stops. Collecting demographic data at the traffic analysis zone or census tract level is too broad to calculate the benefit of bus stop locations. Demographic data needs to be collected at a finer level such as census block. Obtaining demographic data from the U.S. Census Bureau at the census block level produces a challenge because a majority of data is not readily available at this level.

The task of calibrating a large microscopic traffic networks is a task that requires the user to be familiar with the traffic conditions of the case study area and an ample amount of time to reconstruct the traffic conditions. Calibration is a very time consuming task and was a notable limitation in this research. The task of establishing origin and destinations does not take into account the travel path of vehicles, leaving the route choice model to determine vehicle paths. Traffic simulation includes a considerable uncertainty as it attempts to model human behavior which is very random, especially while simulating an evacuation scenario.

6.3 Recommendations for Future Work

There are a few recommendations that would be given if this work was to be furthered. Devise some sort of penalty for bus stops that are located to close to each other to avoid clustering to add in the optimization formulation. Or develop further grouping of TAZ to reduce the effects of clustering. A grid grouping method was introduced in this research but did not sufficiently separate the evacuation bus stop locations.

The relationship/correlation between demographic groups could be explored further in order to avoid over-emphasizing individuals that fall into multiple categories. Other implementations could include new target demographic groups. Census data for the specific demographic groups could be collect on the census block level instead of applying a percentage to the total population of the census block.

The simulation portion of this research could be extended to explore more possibilities for evacuation planning. Different evacuation bus routes could be simulated as well as different headways, and frequencies in which the buses depart or pick up evacuees. This research was limited to selecting optimum evacuation bus stop locations that currently acted as bus stops in the everyday operation of the city. Future work could explore the possibility of using new bus stops that are not currently in use for everyday practice.

APPENDIX

Table 6: Metrorail infrastructure logistics

Jurisdiction	Miles of Track	Stations
District of Columbia	38.30	40
Virginia	38.29	26
Maryland	29.47	20

Table 7: Metrorail car fleet provided by WMATA

Car Type	Number of Cars
Rohr 1000 series	290
Breda 2000/3000 series	364
Breda 4000 series	100
CAF 5000 series	192
Alstom 6000 series	184

Table 8: Metrorail transfer stations

Transfer Station	Train Lines
Fort Totten	red/green
Mt Vernon Square	green/yellow
Gallery PI-Chinatown	yellow/green/red
Stadium-Armory	orange/blue
L'Enfant Plaza	yellow/green
Pentagon	yellow/blue
Metro Center	red/orange/blue
Rosslyn	orange/blue
King Street	yellow/blue

Table 9: Major roadways entering safe zones

Safe Zone	Major Roadway
I	16th St NW
II	7th St NW
III	New York Ave
IV	Pennsylvania Ave SE
V	14th St NW
VI	Constitution Ave NW
VII	E St Expressway
VIII	K St NW & M St NW
IX	Connecticut Ave NW

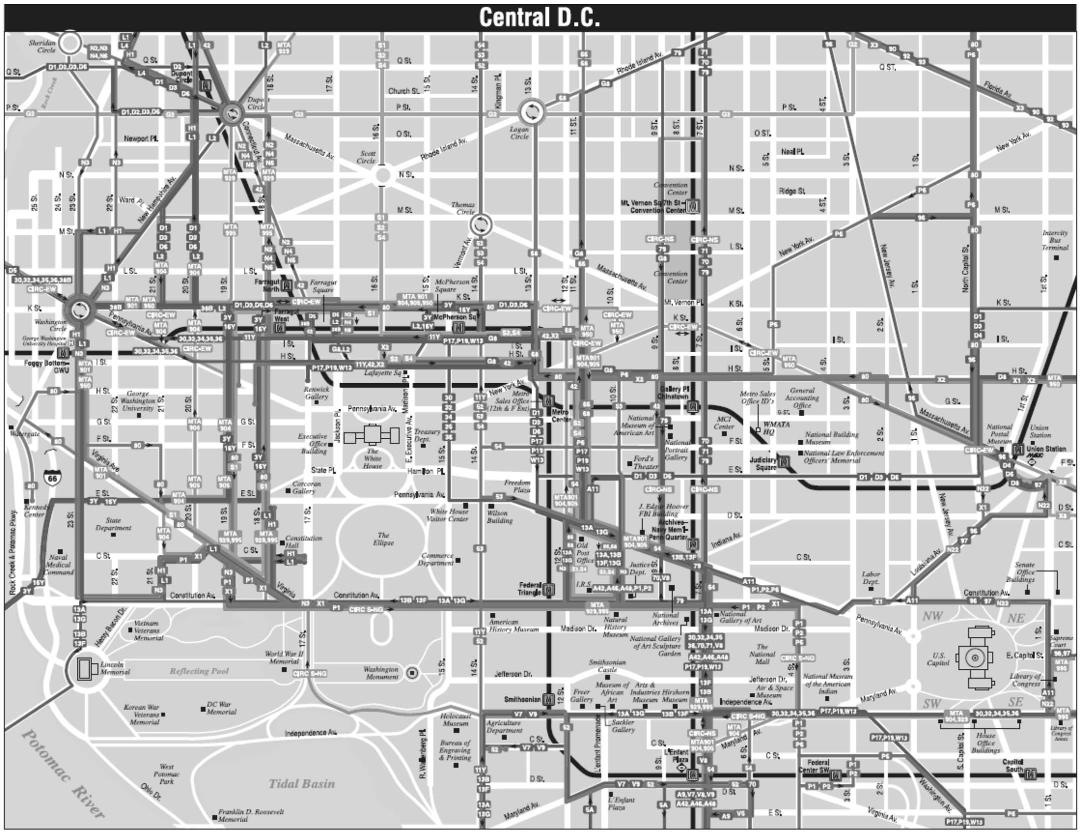

Figure 33 Current bus routes in downtown Washington, D.C. (WMATA)

Table 10: Optimum 20 bus stops

			Weighting Schemes									
Bus stop ID	sum	rank	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	2.10
B66	10	1	1	1	1	1	1	1	1	1	1	1
B67	10	2	1	1	1	1	1	1	1	1	1	1
B74	10	3	1	1	1	1	1	1	1	1	1	1
B95	10	4	1	1	1	1	1	1	1	1	1	1
B104	10	5	1	1	1	1	1	1	1	1	1	1
B133	10	6	1	1	1	1	1	1	1	1	1	1
B134	10	7	1	1	1	1	1	1	1	1	1	1
B160	10	8	1	1	1	1	1	1	1	1	1	1
B168	10	9	1	1	1	1	1	1	1	1	1	1
B91	9	10	1	1	1	1	0	1	1	1	1	1
B186	9	11	1	1	0	1	1	1	1	1	1	1
B218	9	12	1	1	0	1	1	1	1	1	1	1
B220	9	13	1	1	0	1	1	1	1	1	1	1
B125	8	14	1	1	0	1	1	1	1	1	1	0
B13	6	15	1	1	1	1	0	1	0	0	1	0
B68	5	16	0	0	0	1	0	1	1	1	1	0
B72	5	17	1	1	1	0	1	0	0	0	0	1
B161	5	18	1	1	1	0	1	0	0	0	0	1
B162	5	19	0	0	0	1	0	1	1	1	1	0
B210	5	20	0	0	1	0	1	1	1	1	0	0
B219	5	21	1	1	1	1	0	0	0	0	1	0
B273	5	22	1	1	1	0	1	0	0	0	0	1
B46	4	23	1	1	1	0	0	0	0	0	1	0
B188	4	24	0	0	0	1	0	1	1	1	0	0
B234	4	25	0	0	0	1	0	1	1	1	0	0
B366	3	26	0	0	1	0	1	0	0	0	0	1
B375	3	27	0	0	1	0	1	0	0	0	0	1
B183	2	28	0	0	0	0	0	0	1	1	0	0
B211	2	29	0	0	1	0	0	0	0	0	0	1
B303	2	30	0	0	0	0	1	0	0	0	0	1
B78	1	31	0	0	0	0	0	0	0	0	1	0

Table 11: Optimum 40 bus stops

			Weighting Schemes									
Bus stop ID	**sum**	**rank**	**4.1**	**4.2**	**4.3**	**4.4**	**4.5**	**4.6**	**4.7**	**4.8**	**4.9**	**4.10**
B9	10	1	1	1	1	1	1	1	1	1	1	1
B13	10	2	1	1	1	1	1	1	1	1	1	1
B38	10	3	1	1	1	1	1	1	1	1	1	1
B46	10	4	1	1	1	1	1	1	1	1	1	1
B56	10	5	1	1	1	1	1	1	1	1	1	1
B66	10	6	1	1	1	1	1	1	1	1	1	1
B67	10	7	1	1	1	1	1	1	1	1	1	1
B74	10	8	1	1	1	1	1	1	1	1	1	1
B91	10	9	1	1	1	1	1	1	1	1	1	1
B95	10	10	1	1	1	1	1	1	1	1	1	1
B104	10	11	1	1	1	1	1	1	1	1	1	1
B106	10	12	1	1	1	1	1	1	1	1	1	1
B125	10	13	1	1	1	1	1	1	1	1	1	1
B133	10	14	1	1	1	1	1	1	1	1	1	1
B134	10	15	1	1	1	1	1	1	1	1	1	1
B144	10	16	1	1	1	1	1	1	1	1	1	1
B160	10	17	1	1	1	1	1	1	1	1	1	1
B168	10	18	1	1	1	1	1	1	1	1	1	1
B183	10	19	1	1	1	1	1	1	1	1	1	1
B186	10	20	1	1	1	1	1	1	1	1	1	1
B188	10	21	1	1	1	1	1	1	1	1	1	1
B205	10	22	1	1	1	1	1	1	1	1	1	1
B223	10	23	1	1	1	1	1	1	1	1	1	1
B234	10	24	1	1	1	1	1	1	1	1	1	1
B271	10	25	1	1	1	1	1	1	1	1	1	1
B78	9	26	1	1	0	1	1	1	1	1	1	1
B218	9	27	1	1	0	1	1	1	1	1	1	1
B220	9	28	1	1	0	1	1	1	1	1	1	1
B251	9	29	1	1	0	1	1	1	1	1	1	1
B253	9	30	1	1	1	0	1	1	1	1	1	1
B246	8	31	1	0	0	1	1	1	1	1	1	1
B273	8	32	1	1	1	0	1	1	1	0	1	1
B119	7	33	1	1	1	1	0	1	0	0	1	1
B240	7	34	1	1	1	1	0	1	0	1	1	0
B366	7	35	1	1	1	0	1	0	1	0	1	1
B375	7	36	1	1	1	0	1	0	1	0	1	1
B68	5	37	0	0	0	1	0	1	1	1	1	0
B72	5	38	1	1	1	0	1	0	0	0	0	1
B161	5	39	1	1	1	0	1	0	0	0	0	1

B162	5	40	0	0	0	1	0	1	1	1	1	0
B219	5		1	1	1	1	0	0	0	0	1	0
B303	5		1	1	1	0	1	0	0	0	0	1
B310	5		0	0	0	1	0	1	1	1	1	0
B315	5		0	0	0	1	1	1	1	1	0	0
B2	4		0	0	1	1	0	1	0	1	0	0
B210	4		0	0	0	0	1	1	1	1	0	0
B28	3		0	1	1	0	0	0	0	0	0	1
B118	3		0	0	0	0	1	0	1	1	0	0
B211	2		0	0	1	0	0	0	0	0	0	1
B274	2		0	0	0	1	0	0	0	1	0	0
B58	1		0	0	1	0	0	0	0	0	0	0
B80	1		0	0	1	0	0	0	0	0	0	0
B254	1		0	0	0	1	0	0	0	0	0	0

Table 12: Optimum 60 bus stops

	Weighting Schemes											
Bus stop ID	**sum**	**rank**	**6.1**	**6.2**	**6.3**	**6.4**	**6.5**	**6.6**	**6.7**	**6.8**	**6.9**	**6.10**
B2	10	1	1	1	1	1	1	1	1	1	1	1
B9	10	2	1	1	1	1	1	1	1	1	1	1
B13	10	3	1	1	1	1	1	1	1	1	1	1
B28	10	4	1	1	1	1	1	1	1	1	1	1
B36	10	5	1	1	1	1	1	1	1	1	1	1
B38	10	6	1	1	1	1	1	1	1	1	1	1
B46	10	7	1	1	1	1	1	1	1	1	1	1
B56	10	8	1	1	1	1	1	1	1	1	1	1
B58	10	9	1	1	1	1	1	1	1	1	1	1
B66	10	10	1	1	1	1	1	1	1	1	1	1
B67	10	11	1	1	1	1	1	1	1	1	1	1
B74	10	12	1	1	1	1	1	1	1	1	1	1
B91	10	13	1	1	1	1	1	1	1	1	1	1
B95	10	14	1	1	1	1	1	1	1	1	1	1
B104	10	15	1	1	1	1	1	1	1	1	1	1
B106	10	16	1	1	1	1	1	1	1	1	1	1
B125	10	17	1	1	1	1	1	1	1	1	1	1
B133	10	18	1	1	1	1	1	1	1	1	1	1
B134	10	19	1	1	1	1	1	1	1	1	1	1
B144	10	20	1	1	1	1	1	1	1	1	1	1
B157	10	21	1	1	1	1	1	1	1	1	1	1
B160	10	22	1	1	1	1	1	1	1	1	1	1
B168	10	23	1	1	1	1	1	1	1	1	1	1
B183	10	24	1	1	1	1	1	1	1	1	1	1
B186	10	25	1	1	1	1	1	1	1	1	1	1

B188	10	26	1	1	1	1	1	1	1	1	1	1
B190	10	27	1	1	1	1	1	1	1	1	1	1
B205	10	28	1	1	1	1	1	1	1	1	1	1
B223	10	29	1	1	1	1	1	1	1	1	1	1
B234	10	30	1	1	1	1	1	1	1	1	1	1
B240	10	31	1	1	1	1	1	1	1	1	1	1
B246	10	32	1	1	1	1	1	1	1	1	1	1
B266	10	33	1	1	1	1	1	1	1	1	1	1
B271	10	34	1	1	1	1	1	1	1	1	1	1
B282	10	35	1	1	1	1	1	1	1	1	1	1
B315	10	36	1	1	1	1	1	1	1	1	1	1
B326	10	37	1	1	1	1	1	1	1	1	1	1
B359	10	38	1	1	1	1	1	1	1	1	1	1
B366	10	39	1	1	1	1	1	1	1	1	1	1
B369	10	40	1	1	1	1	1	1	1	1	1	1
B383	10	41	1	1	1	1	1	1	1	1	1	1
B388	10	42	1	1	1	1	1	1	1	1	1	1
B392	10	43	1	1	1	1	1	1	1	1	1	1
B78	9	44	1	1	0	1	1	1	1	1	1	1
B218	9	45	1	1	0	1	1	1	1	1	1	1
B220	9	46	1	1	0	1	1	1	1	1	1	1
B251	9	47	1	1	0	1	1	1	1	1	1	1
B253	9	48	1	1	1	0	1	1	1	1	1	1
B273	8	49	1	1	1	0	1	1	1	0	1	1
B350	8	50	1	1	1	0	1	1	1	0	1	1
B375	8	51	1	1	1	0	1	1	1	0	1	1
B378	8	52	1	1	1	0	1	1	1	0	1	1
B119	7	53	1	1	1	1	0	1	0	0	1	1
B68	5	54	0	0	0	1	0	1	1	1	1	0
B72	5	55	1	1	1	0	1	0	0	0	0	1
B161	5	56	1	1	1	0	1	0	0	0	0	1
B162	5	57	0	0	0	1	0	1	1	1	1	0
B210	5	58	0	0	1	0	1	1	1	1	0	0
B303	5	59	1	1	1	0	1	0	0	0	0	1
B310	5	60	0	0	0	1	0	1	1	1	1	0
B332	5		1	1	1	0	0	0	0	0	1	1
B333	5		0	0	0	1	1	1	1	1	0	0
B339	5		0	0	0	1	0	1	1	1	1	0
B340	5		1	1	1	0	1	0	0	0	0	1
B342	5		0	0	0	1	0	1	1	1	1	0
B346	5		1	1	1	0	1	0	0	0	0	1
B219	4		0	1	1	1	0	0	0	0	1	0

B118	3		0	0	0	0	1	0	1	1	0	0
B211	3		1	0	1	0	0	0	0	0	0	1
B274	2		0	0	0	1	0	0	0	1	0	0
B349	2		0	0	0	1	0	0	0	1	0	0
B374	2		0	0	0	1	0	0	0	1	0	0
B380	2		0	0	0	1	0	0	0	1	0	0
B80	1		0	0	1	0	0	0	0	0	0	0
B249	1		0	0	1	0	0	0	0	0	0	0
B254	1		0	0	0	1	0	0	0	0	0	0

Table 13: Optimum bus stops for all scenarios

20stops	30stops	40stops	50stops	60stops
B67	B13	B9	B2	B2
B74	B66	B13	B9	B9
B95	B67	B46	B13	B13
B104	B74	B56	B28	B28
B133	B91	B66	B38	B36
B134	B95	B67	B46	B38
B160	B104	B74	B56	B46
B168	B125	B91	B66	B56
B326	B133	B95	B67	B58
B359	B134	B104	B74	B66
B186	B160	B125	B91	B67
B218	B168	B133	B95	B74
B220	B186	B134	B104	B91
B66	B188	B144	B106	B95
B366	B234	B160	B125	B104
B28	B326	B168	B133	B106
B72	B359	B183	B134	B125
B161	B78	B186	B144	B133
B219	B218	B188	B160	B134
B273	B220	B205	B168	B144
	B46	B234	B183	B157
	B183	B326	B186	B160
	B366	B359	B188	B168
	B144	B78	B205	B183
	B28	B218	B223	B186
	B273	B220	B234	B188
	B72	B253	B240	B190
	B161	B271	B246	B205
	B219	B273	B266	B223
	B375	B366	B271	B234

		B251	B282	B240
		B28	B315	B246
		B38	B326	B266
		B106	B359	B271
		B119	B58	B282
		B72	B78	B315
		B161	B190	B326
		B219	B218	B359
		B303	B220	B366
		B375	B251	B369
			B253	B383
			B366	B388
			B273	B392
			B375	B78
			B119	B218
			B36	B220
			B72	B251
			B161	B253
			B219	B273
			B303	B350
				B375
				B378
				B119
				B72
				B161
				B219
				B303
				B332
				B340
				B346

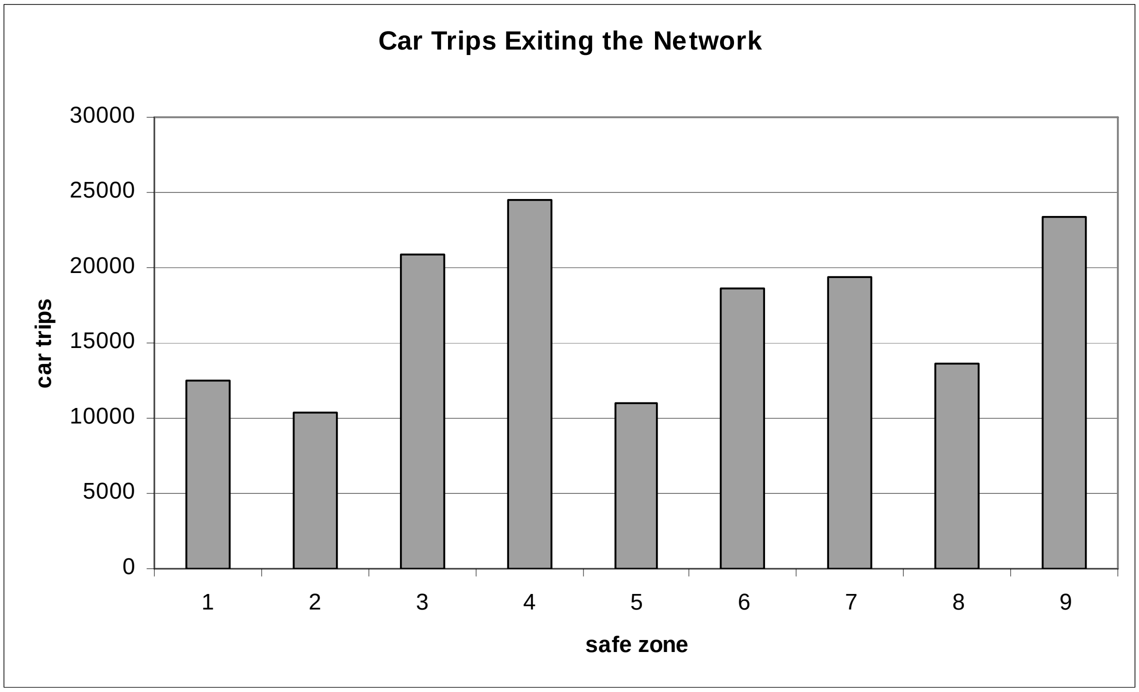

Figure 34 Car trips exiting the network

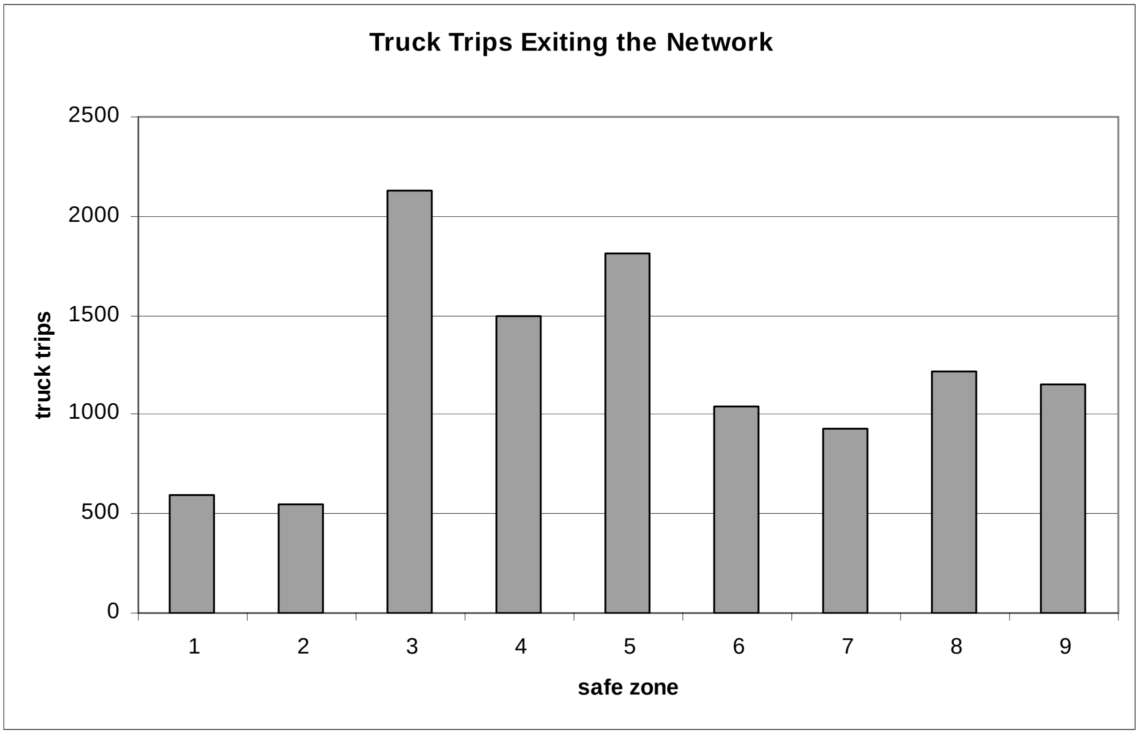

Figure 35 Truck trips exiting the network

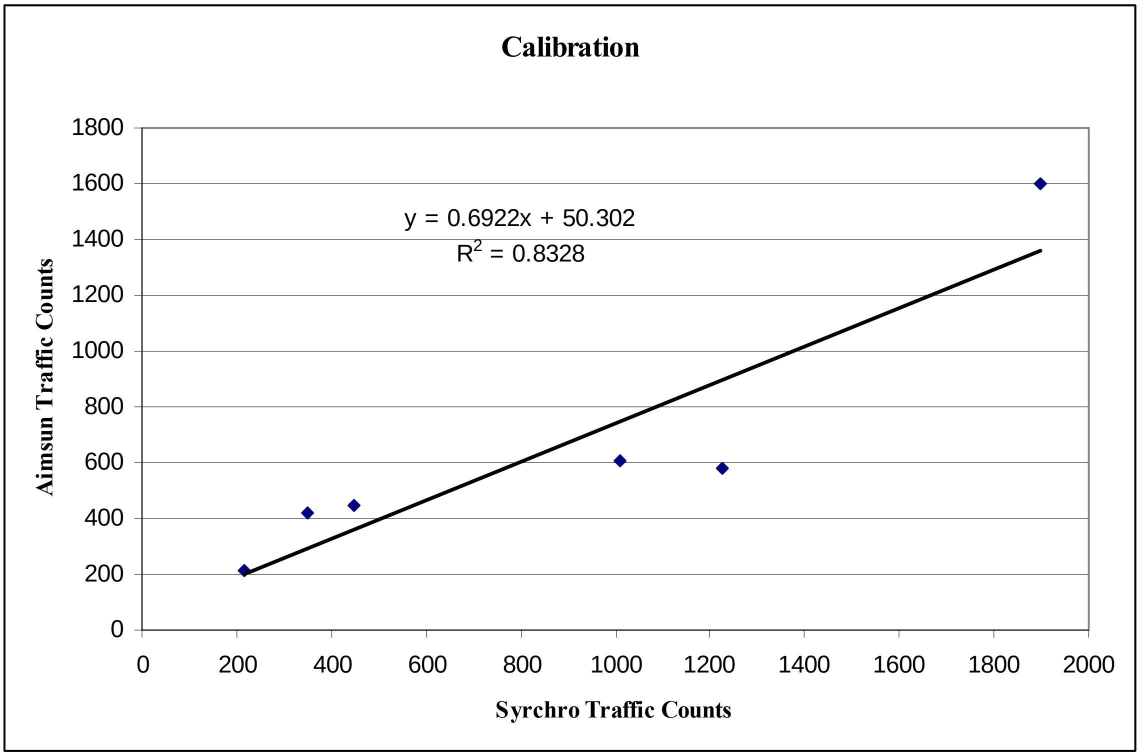

Figure 36 Calibration trial 1

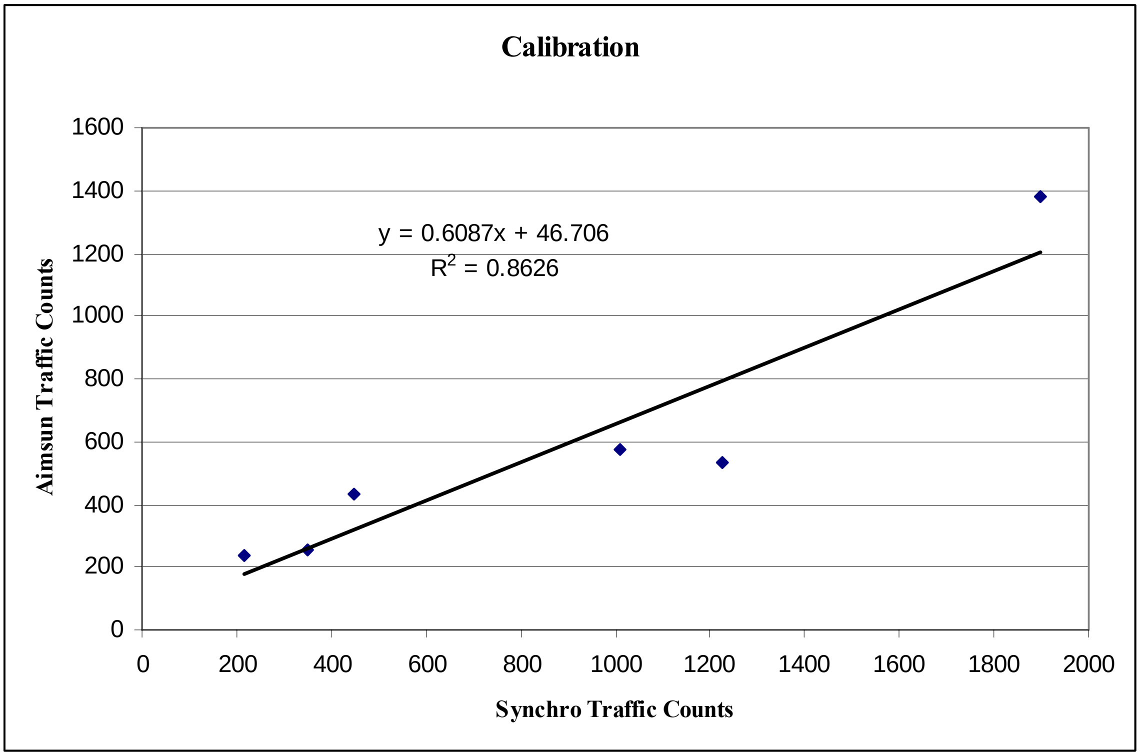

Figure 37 Calibration trial 2

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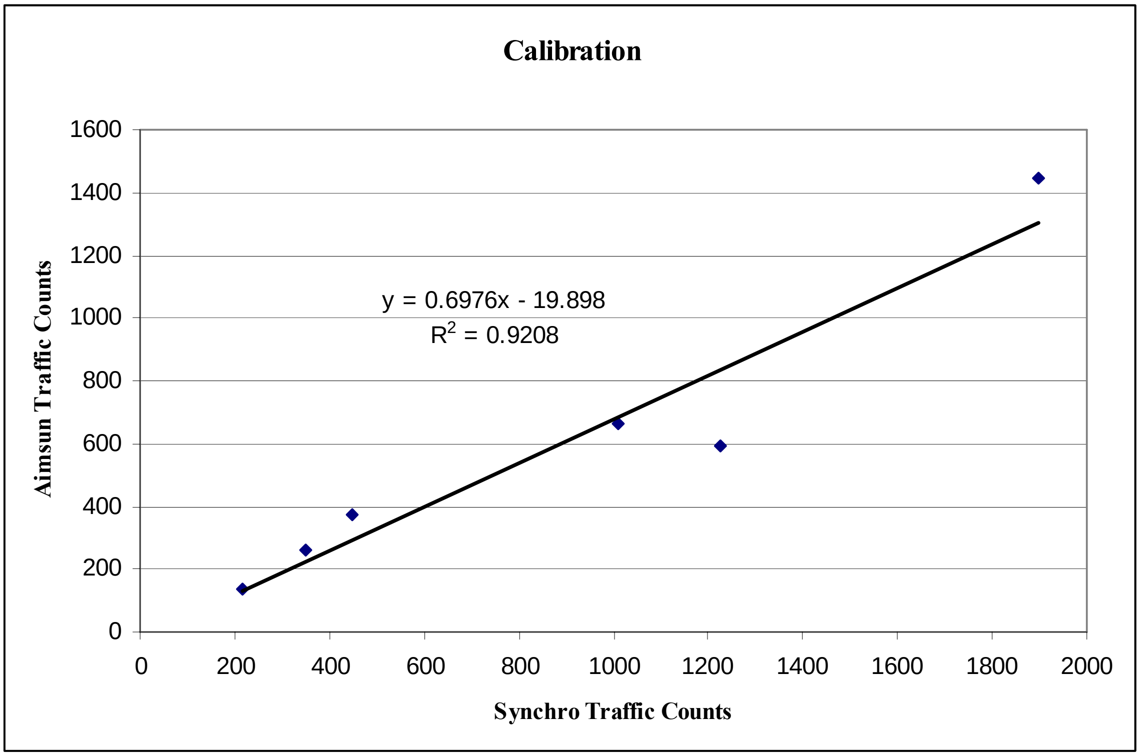

Figure 38 Calibration trial 3

Table 14: Replication results for delay time

Delay Time						
max number of stops	1	2	3	4	5	Average
20	304.9500	316.8800	323.7080	293.2180	305.4180	308.8348
30	303.0150	303.0150	334.4230	320.3780	316.2170	315.4096
40	297.4840	308.7490	312.4250	364.8990	332.1250	323.1364
50	289.6400	274.4120	294.4130	300.3200	276.4660	287.0502
60	263.4640	282.1530	289.5380	280.9650	275.6950	278.3630

Table 15: Replication results for stop time

Stop Time						
max number of stops	1	2	3	4	5	Average
20	276.3660	289.5660	297.1250	270.2940	279.8580	282.6418
30	278.1860	278.8617	309.0430	292.1400	288.2570	289.2975
40	272.4660	280.9250	285.6800	339.1110	306.5860	296.9536
50	262.8070	248.4450	267.1350	276.6740	250.6820	261.1486
60	237.9410	256.7340	271.0770	254.5180	248.7960	253.8132

Table 16: Replication results for total distance traveled

Total Distance Traveled						
max number of stops	1	2	3	4	5	Average
20	85.4400	116.9100	84.1900	84.1647	92.8012	92.7012
30	172.4640	172.4640	139.7310	129.2480	129.0990	148.6012
40	201.8200	168.8200	185.4970	214.7490	204.5140	195.0800
50	219.5030	230.6100	246.2470	250.3490	208.5220	231.0462
60	275.2090	299.6880	265.2950	294.0630	267.4850	280.3480

Table 17: Replication results for total travel time

Total Travel Time						
max number of stops	1	2	3	4	5	Average
20	7.9600	10.9000	8.4200	7.7115	8.5405	8.7064
30	11.2376	9.8470	9.5063	11.3030	10.1121	10.4012
40	18.5331	15.9490	16.9813	21.3864	20.3889	18.6477
50	19.6600	20.4644	23.1290	23.1785	18.5718	21.0007
60	23.8234	26.9579	24.0743	26.3718	23.3058	24.9066

Table 18: Replication results for travel time

Travel Time						
max number of stops	1	2	3	4	5	Average
20	381.2000	391.9100	399.2570	368.3680	381.4440	384.4358
30	378.2540	378.2540	409.2590	395.4300	391.4850	390.5364
40	372.9210	383.6340	388.0160	556.5450	407.2420	421.6716
50	364.6600	349.3600	370.1970	375.9570	351.6610	362.3670
60	339.3190	358.3510	373.1270	357.1650	350.7540	355.7432

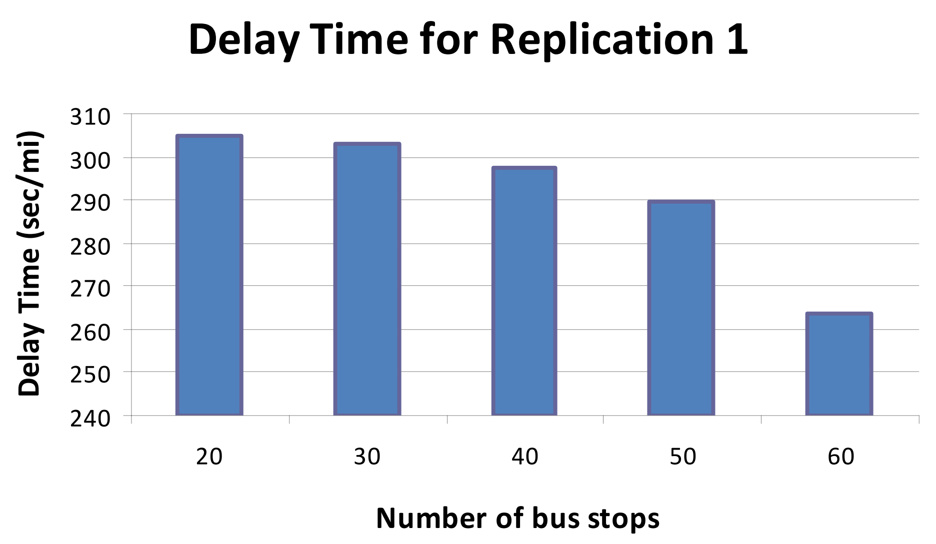

Figure 39 Delay time for replication 1

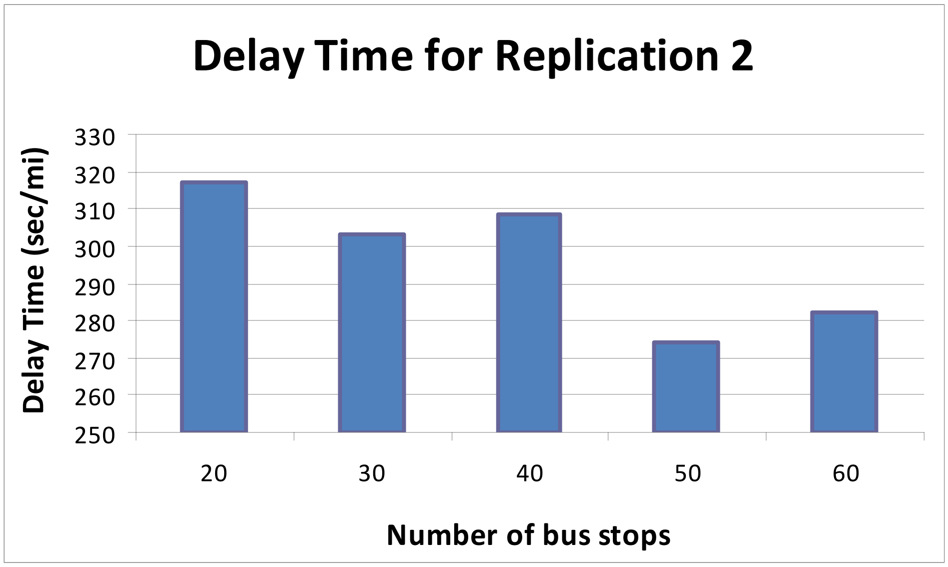

Figure 40 Delay time for replication 2

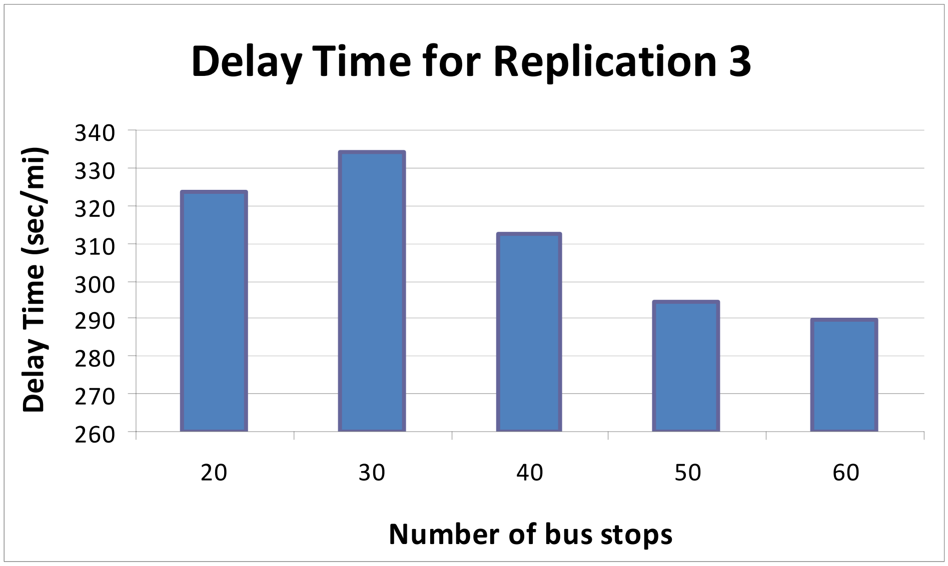

Figure 41 Delay time for replication 3

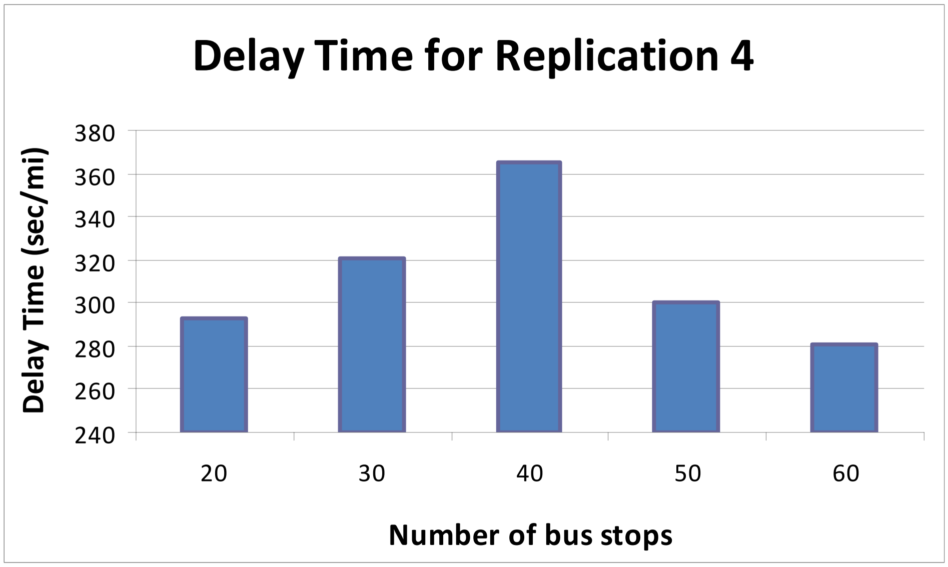

Figure 42 Delay time for replication 4

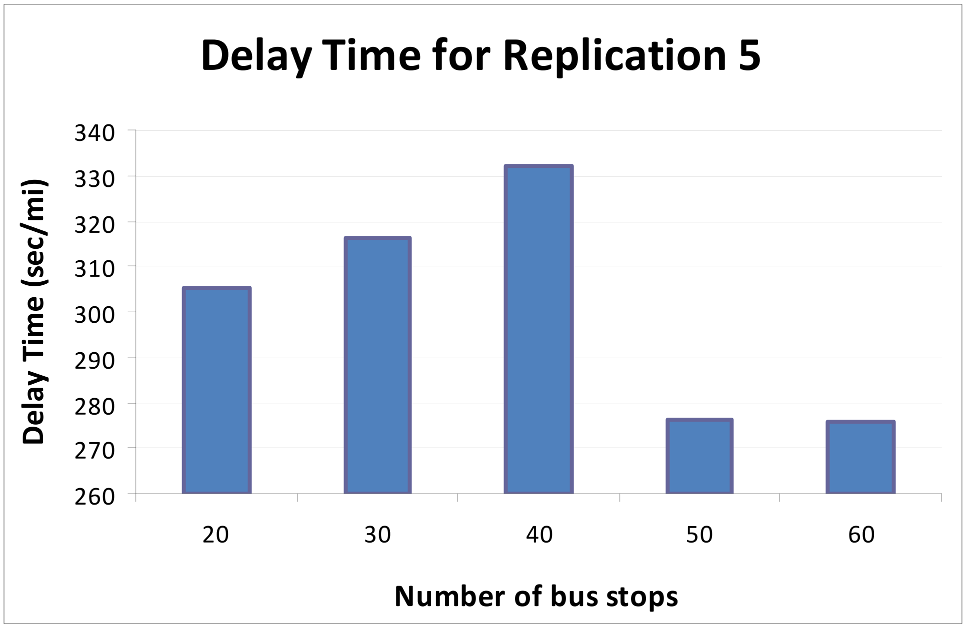

Figure 43 Delay time for replication 5

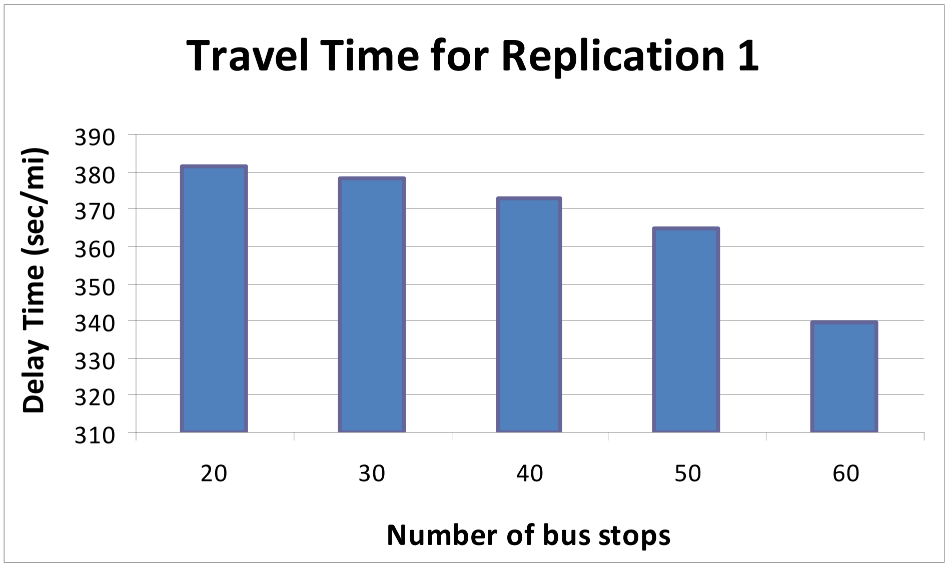

Figure 44 Travel time for replication 1

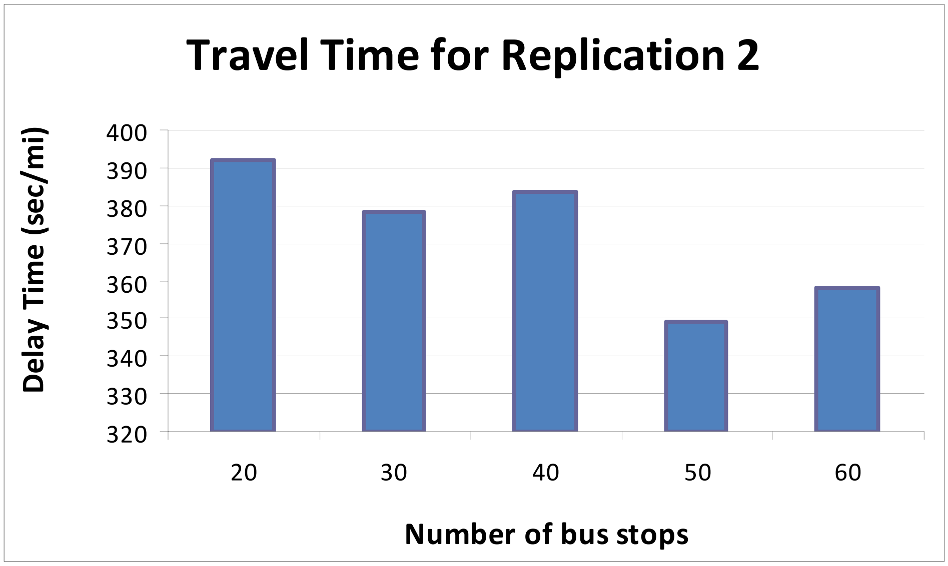

Figure 45 Travel time for replication 2

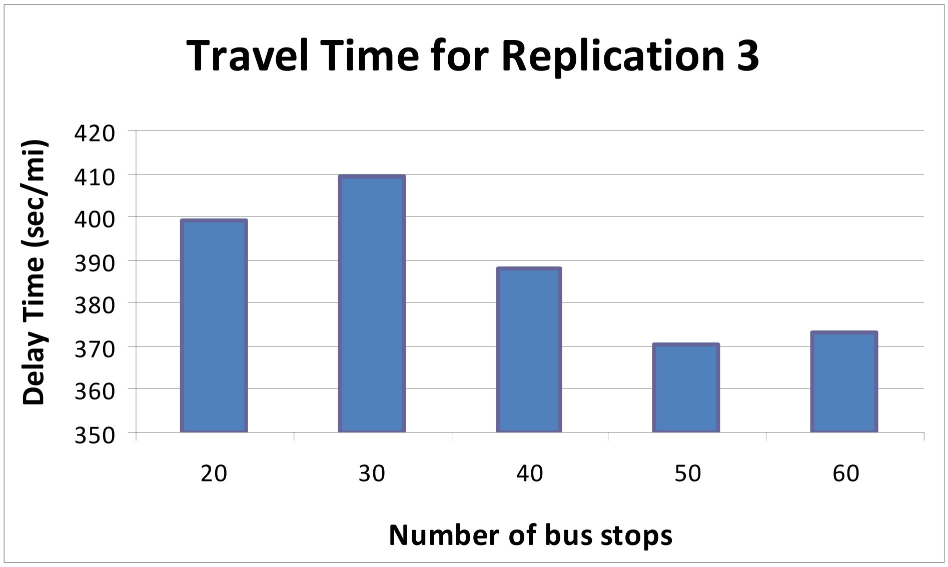

Figure 46 Travel time for replication 3

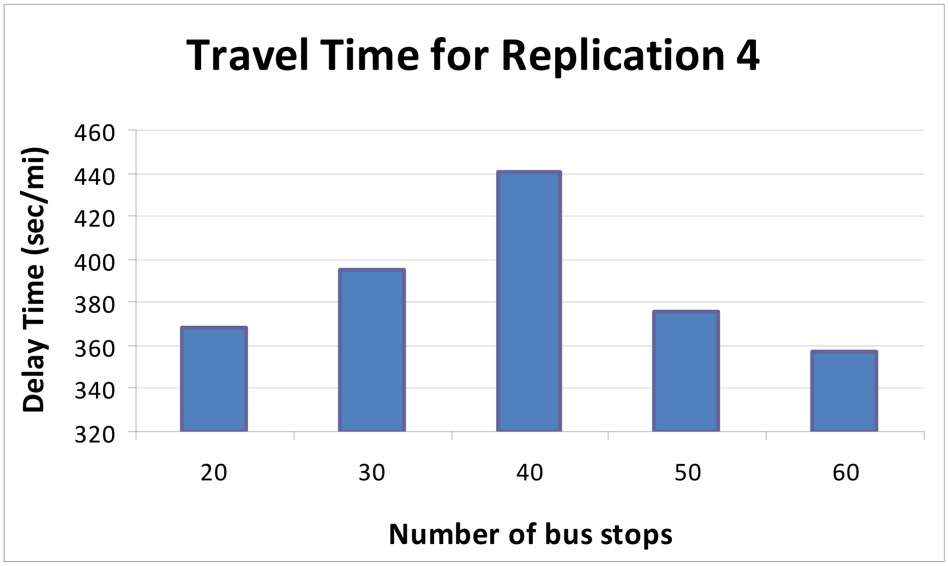

Figure 47 Travel time for replication 4

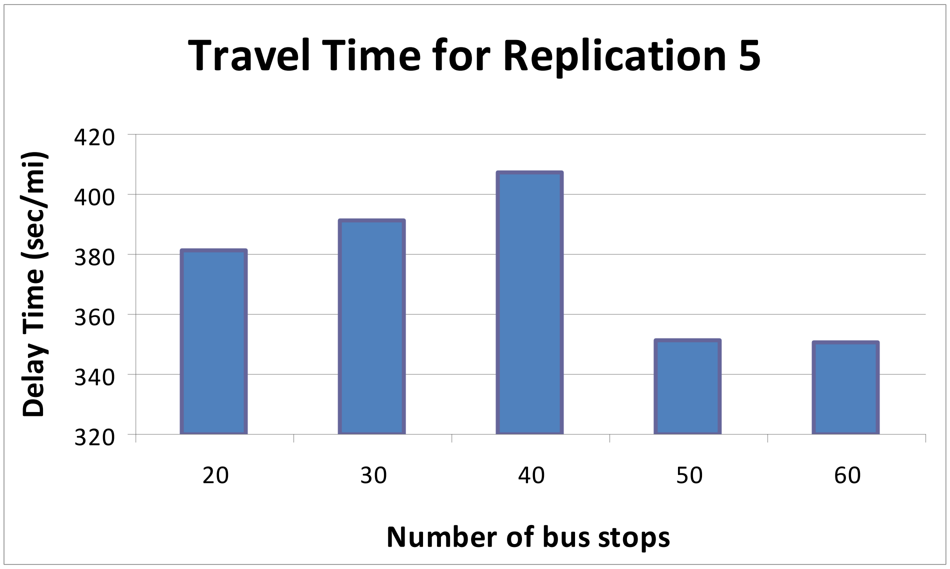

Figure 48 Travel time for replication 5

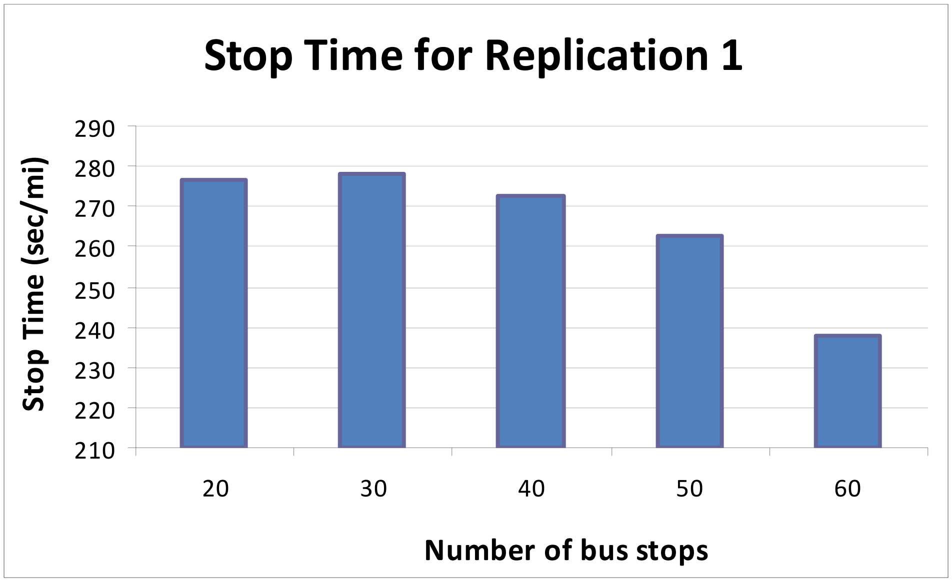

Figure 49 Stop time for replication 1

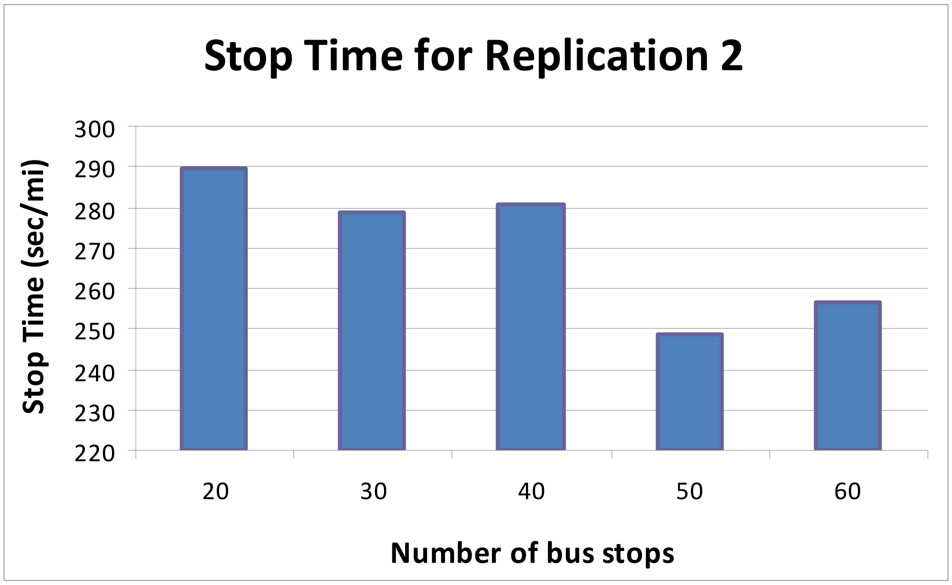

Figure 50 Stop time for replication 2

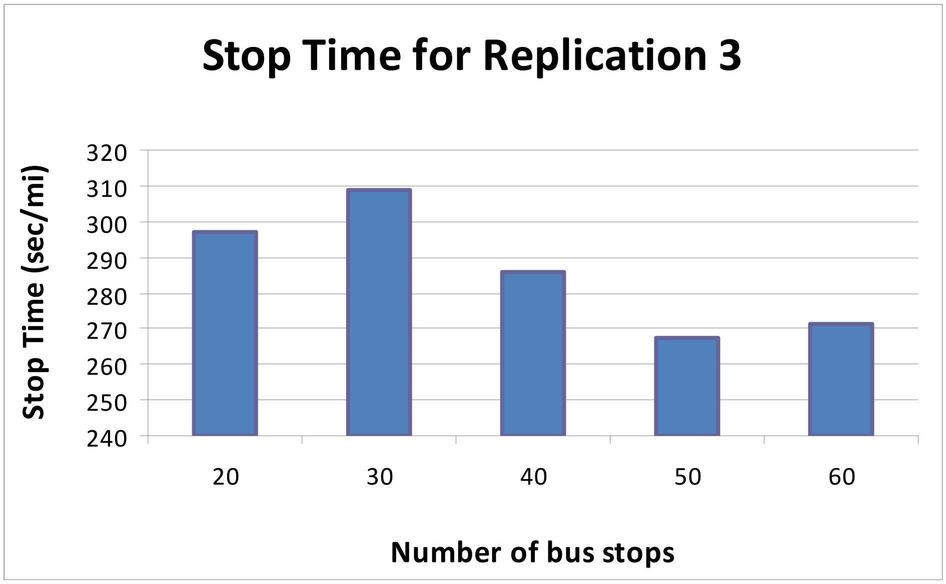

Figure 51 Stop time for replication 3

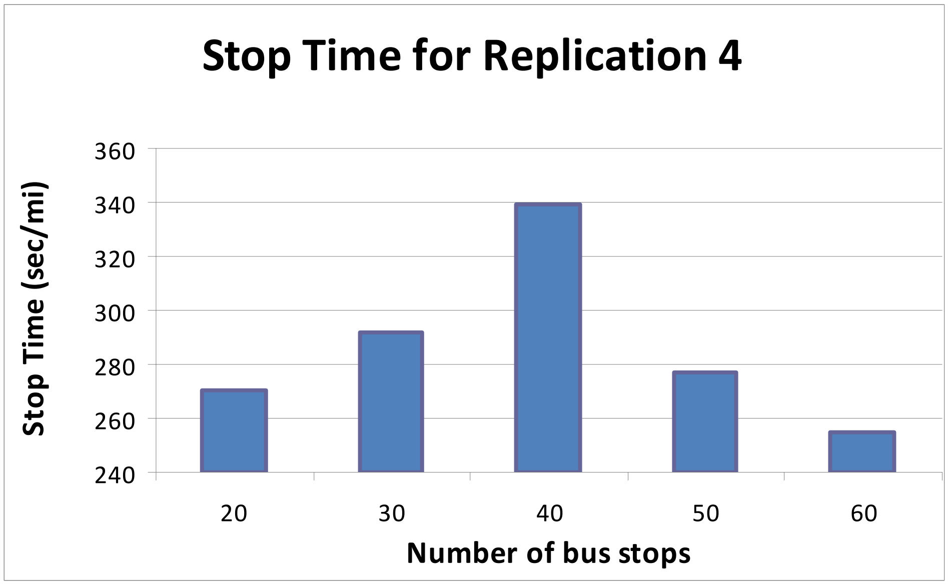

Figure 52 Stop time for replication 4

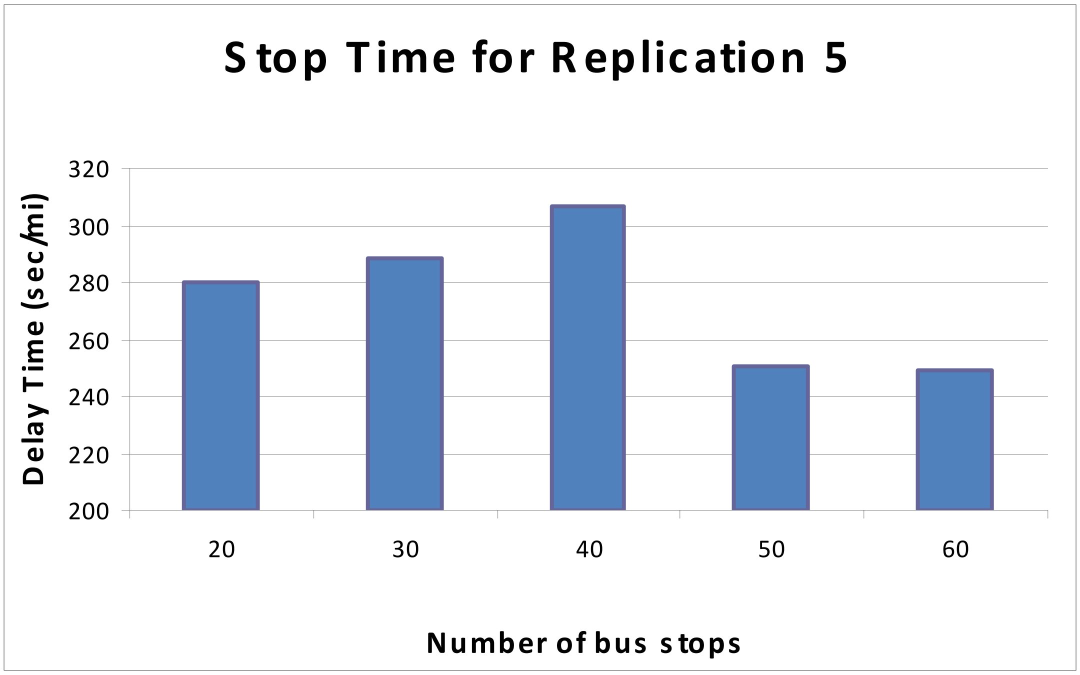

Figure 53 Stop time for replication 5

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