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Preparedness and Catastrophic Event Management for the Washington, D.C. Metropolitan Area

DECEMBER 2010

FTA Report No. 0007
Federal Transit Administration

PREPARED BY

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U.S. Department of Transportation
Federal Transit Administration

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U.S. Department of Transportation
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Metric Conversion Table

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
^{o}F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^{o}C

REPORT DOCUMENTION PAGE	*Form Approved* *OMB No. 07-0188*

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY	2. REPORT DATE December 2010	3. REPORT TYPE AND DATES COVERED January 2007-December 2010

4. TITLE AND SUBTITLE Preparedness and Catastrophic Event Management for the Washington, D.C. Metropolitan Area	5. FUNDING NUMBERS FL-26-7102
6. AUTHOR(S) Dr. Evangelos I. Kaisar, Dr. P.D. Scarlatos	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESSE(ES) Center for Intermodal Transportation Safety and Security Florida Atlantic University 777 Glades Road Boca Raton, FL 33431	8. PERFORMING ORGANIZATION REPORT NUMBER FTA Report No. 0007
SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Department of Transportation Federal Transit Administration East Building 1200 New Jersey Avenue, SE Washington, DC 20590	10. SPONSORING/MONITORING AGENCY REPORT NUMBER FTA Report No. 0007
11. SUPPLEMENTARY NOTES	
12A. DISTRIBUTION/AVAILABILITY STATEMENT	12B. DISTRIBUTION CODE TRI-20

13. ABSTRACT

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This project is an accumulation of three separate case studies that were conducted in the Washington, D.C. downtown area with various degrees of specification. The purpose of this research is to examine and assess the existing infrastructure's ability to handle specified disasters and to make recommendations based upon the findings of this research.

14. SUBJECT TERMS Traffic analysis zones (TAZ), centroids, origin-destination (O-D) matrices, safe zone, special needs populations, signal priority, red truncation, green extension	15. NUMBER OF PAGES 109
16. PRICE CODE	

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UU

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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EXECUTIVE SUMMARY

The devastating effects of terrorism are distinctly clear and realistic to our generation with the haunting September 11 attacks, the 2005 subway bombings in London, the 2009 attempted Christmas attack, and constant turmoil overseas. Therefore, it is important to examine and assess the outcome of potential terrorist attacks in preparation for an emergency evacuation by minimizing damages and enhancing solutions for the safety of the public. More specifically, there is a need to investigate the ways in which a terrorist attack could affect a transportation network in densely populated areas and develop efficient emergency evacuation plans. Since 2007, Florida Atlantic University's Transportation Research Group has developed several emergency management scenarios involving immediate aftermaths of terrorist attacks in Washington, D.C.

This project is an accumulation of three separate case studies that were conducted in the Washington, D.C. downtown area with various degrees of specification. The first project completed was a study of emergency evacuation techniques to assess the existing infrastructure's ability to safely, securely, and efficiently evacuate impacted segments of the Washington D.C. metropolitan area. An emergency scenario was examined at Union Station, a heavily-used transit/metro station recommended for examination by the Washington Metropolitan Area Transit Authority (WMATA). The affected surrounding area was evacuated as a result of an unspecified terrorist attack that prohibited the use of underground transit rails. In addition to the evacuation of vehicles in the network, the influx of the underground rail commuters must be evacuated using other forms of transit such as bus and ground-level rail systems.

To examine the area, a series of evacuation techniques was applied and compared for efficiency. The assessed techniques for the case study included staged evacuation, police-assisted contraflow, and public transit priority lanes. In addition, multiple combinations of these evacuation techniques were used to provide researchers with more information regarding the potential benefits of evacuation strategies. In the evaluation of the efficiency of the evacuation techniques, micro-simulation traffic software was used. The software displays a realistic representation of the temporal and spatial interactions during the process of the evacuation. Through the use of this powerful micro-simulator, evacuation strategies were generated, implemented, and compared for analysis.

The results of this study found that the majority (63–65%) of able people within the impact area with no access to a personal vehicle will walk to a safe destination, another 20–22 percent will attempt to drive, and the remaining 15–17 percent will rely on emergency evacuation by buses to a safe area. The total evacuation time found through the simulation model was approximately one hour to evacuate persons who choose to drive, walk, or take the emergency evacuation buses.

The second study concentrated this original research on a finite group of people—populations with special needs. The need for evacuation plans in place for special needs populations, in particular, became evident after catastrophic events such as Hurricane Katrina. For the purpose of this segment of the study, special needs populations include but are not limited to people with physical disabilities, older adults, non-English-speaking persons, residents and employees without vehicles, and tourists with limited spatial knowledge of the area.

The main objective was to evaluate different evacuation procedures for special needs populations from large urban areas using current public transit systems. A hybrid micro-mesoscopic simulation model was constructed to investigate real-life scenarios for evacuation methodologies. The core area of the network was developed as a microscopic model to analyze in detail the effects of an attack in the immediate surrounding area of Union Station, where the outer region used a mesoscopic formulation to examine a more general impact. A linear programming optimization model was then developed to find the optimum locations for evacuation bus stops. The results of this aspect of the study identified specific bus stops for emergency evacuation of special needs populations and the associated bus routes to safe zones.

The final segment of research conducted with a case study of Washington, D.C. explores the feasibility of the use of transit signal priority (TSP) during a mass evacuation where police assistance is unavailable. Standard practice for emergency evacuation consists of the placement of police officers at intersections throughout the evacuation area. However, this is not always an option where environmental factors such as the presence of a fire, chemical plume, or radioactive fallout (nuclear-contaminated wind and dust) do not permit police presence. A major assumption of this case study was that public transit services used in this emergency evacuation scenario are operated by trained emergency response professionals wearing protective gear to prevent contact with hazardous material.

The results of this study found that it would take four non-prioritized transit units to accomplish the same task as three prioritized vehicles. Furthermore, allowing TSP during an urban evacuation has little to no effect on evacuation clearance time or evacuee travel time. Moreover, when TSP is restricted to operate only on evacuation routes, travel time and delay time both decrease.

SECTION 1

Introduction

Due to intense focus on terrorist attacks and other potential emergency situations, evacuation techniques and procedures have gained increased attention in the last decade. Extensive research has been conducted to maximize the potential of emergency routes and minimize damages generated from an emergency incident. This research presents an emergency technique for evacuation of the Washington, D.C. metropolitan area.

According to the Transportation Research Board (2008), the extent to which transit can be a successful partner in any evacuation depends on whether a good local emergency response and evacuation plan is in place. It is, therefore, important to evaluate the existing infrastructure and develop efficient and effective emergency evacuation plans for the safety of the public in densely-populated areas. Transit can play a vital role for the efficiency of emergency evacuation. For example, during the terrorist attack on the World Trade Center on September 11, 2001, transit agencies were heavily involved in the evacuation of people and also for the transport of employees and equipment to support emergency responders in the impacted area. Also, in Washington, D.C., Metrorail became the preferred mode for transport from congested areas following the strike on the Pentagon. The contrary was, unfortunately, a fact for citizens without a vehicle in New Orleans during the evacuation of residents in advance of Hurricane Katrina. Thousands of citizens were left in danger due to the inexistence of transit or failure to implement existing plans (TRB 2008). These are examples that reveal the importance of well-established emergency evacuation plans that incorporate transit as an essential mode for the success of the execution.

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 is 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 paths 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 so 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 disasters, biological threats, chemical threats, and terrorist threats. Depending on the 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 cause great destruction and require more planning and action than just sheltering in place. Potential hazards that result in major loss of life and destruction of infrastructure require populations to leave harm's 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). 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 (TRB 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 that proper communication plans are in effect, not just among emergency officials but 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 loved 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, re-employment, and reuniting with love ones.

Because of the awareness of the affliction caused by possible incidents, growing concerns of evacuation procedures have 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 (DHS 2009). On March 1, 2003 FEMA joined DHS and assumed the responsibility of assisting local and state governments in preparedness and response to disasters (FEMA 2009). Both DHS and FEMA collaborated to create the National Response Framework to advise emergency personnel and 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 among 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 and 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 the focus of ESF#1. The Support Annexes describe common functions such as financial aspects and volunteer needs. 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 wildfires 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 cannot be prevented but are, rather, acts of God, and pre-impact evacuation is one method to reduce devastating impacts. Having fewer people in the impact area allows recovery efforts to be improved by not focusing all attention on providing medical aid and recovering bodies (Perry 1979). No-notice emergency evacuations can result from industrial and 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 immediately from their immediate location (sometimes not allowing time for people to return home to gather 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 on 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. 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 a city ought to be evaluated for evacuation scenarios that best suit the population of the area.

The issue of evacuating special needs populations has become more prevalent with current events such as Hurricane Katrina (Litman 2006). The difficulty in evacuating populations with special needs is based on the extra assistance needed by those individuals: individuals who do not speak English and cannot heed warning messages or evacuation orders; older adults and physically disabled populations that might have a difficult time with mobility and walking to safe zones; and tourist and transit-dependent employees who 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 U.S. Congress's 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 into evacuation plans the needs of persons with disabilities, older adults, and people who do not own personal vehicles. In the past (e.g., Hurricane Katrina), the needs of these populations has been overlooked (Kiefer et al. 2006; He et al. 2009; Litman 2006). The guide addresses how local, territorial, tribal, and state managers should handle the extra requirements for special needs populations under evacuation situations. It discusses solutions such as having a registry for such populations, gathering census data, and using geographic information systems to organize special needs demographics.

The federal government has become extremely aware of the urgency to address special needs 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 the aftermath of Hurricane Katrina. It proposes pre- and post-planning for special needs individuals including low income families, persons with disabilities, the homeless, non-English speaking persons, and older adults.

Special needs populations such as transit-dependent employees and tourists greatly depend on public transportation for mobility. Furthermore, low-income individuals and families may have only one mode of travel: public transit. This study focuses on developing a public transit routing scenario to best serve special needs populations in the downtown core area of Washington, D.C.

Catastrophic events in the past have highlighted the need for more planning, research, and development in the field of emergency preparedness in transportation (Yuan et al. 2009). These events, be they manmade or natural disaster, pose a threat to life and property. Mitigation of risk is an important aspect, but it is impossible to guarantee any level of safety. Disasters will occur, and it is the duty of planners and decision makers to organize, prepare, and coordinate the response. Without proper planning and organization, magnifications of both the immediate and residual adverse effects are inevitable. Improper coordination during an evacuation could lead to otherwise avoidable gridlock and congestion, which may cause a significant loss of life and/or property (Chiu et al. 2004). For this reason, it is imperative that governing agencies produce plans and develop guidelines for the assistance of residents in emergency evacuation, primarily with regard to transportation.

Evacuations in urban areas form the most complex problems for emergency planners. High population densities compounded by limited resources form an overwhelming set of constraints, which force planners to make difficult decisions. Allocations of personnel or resources to one region or subset of the city means less is available to all others. Additionally, many plans in use today are based on broad assumptions and critical reliance on resources, which may not be available when called into action (Kendra et al. 2008). The major problems concerning emergency evacuation are capacity and coordination (Chiu et al. 2004). Capacity is a physical limitation, a constraint that only infrastructure improvements can address. The use of lane reversal, also known as contraflow, is one technique that increases capacity. However, no procedure will ultimately put more asphalt on the roadway to assist in emergency evacuation. Coordination in the form of resource allocation is a challenge with which preparation, planning, and practice have shown to better facilitate operations. Coordination problems in the field of emergency transportation translate to delay—time loss that could have otherwise been used to save lives. However, advancements in technology have led to life-saving breakthroughs (Chiu et al. 2004).

Transportation researchers and engineers have developed many different types of solutions to these coordination problems, such as intelligent transportation systems (ITS). ITS can assist via variable message signs (VMS) and signal control in the event of an emergency. Signal timing greatly effects emergency management and response during an evacuation (Chen 2007). There exist several different types of signal controls in practice today. The basic pre-timed signal setting allows traffic to flow for a predetermined amount of time for each right-of-way. Actuated signals use detectors or sensors to capture data from the intersection and use this information to modify the control settings. Adaptive controls are network-based controls, which not only modify the individual splits of an intersection but also have the ability to change offset and cycle length. Each signal control strategy has different advantages and drawbacks that can greatly influence traffic flow and operations. Proper coordination can also assist with scheduling and personnel allocation. Advancements in the field of geographic information systems (GIS) have further diversified the tools with which planners have available to assist in the evacuation effort (Pal et al. 2005). Traffic simulation tools are being used worldwide to test the effectiveness of different evacuation procedures (Chiu 2004; Pal et al. 2005; Yuan et al. 2009). With the computational abilities available on the market, software such as these is becoming more advanced and capable of modeling larger areas with more detail and accuracy than ever before.

SECTION 2

Case Study 1: Emergency Evacuation Methodologies Using Public Transit with Micro-Simulation Modeling

Methodology

Case Description

An unspecified underground terrorist attack at Union Station was examined to assess the existing infrastructure's ability to efficiently evacuate the impacted areas in case of a possible terrorist attack. Union Station and Gallery Place/Chinatown Station are approximately one mile apart. In addition to evacuating the vehicles in the network, the influx of the underground rail commuters would be evacuated using other forms of transit such as bus and ground level systems. Transit would play a lead role in the evacuation of the rail commuters. Incidents caused by terrorist attacks require a rapid response. Coordination is required by public transit within the region to move people out of the area safely and efficiently. Emergency situations within the area of study require shifting and movements of available transit at the time of the incident. The amount of available public transit depends on the time of the incident. Heavy congestion is expected during morning and evening peak hours.

Union Station is a high-traffic transportation center of Washington, D.C. where people have access to buses, trains (such as AMTRAK, VRE, and MARK), and Metrorail systems. This combination of traffic modes makes Union Station an essential artery for the mass transit system of the city. The emergency scenario presented in this paper assumes a relatively small explosion that inhibits rail (train or Metro) travel on a workday around 9:00 am for a period of 24 hours. The building would be shut down to the public immediately following the evacuation of all station inhabitants and the population of the direct surrounding area (about 25,000 people based on time of day and severity of incident). The station and surrounding areas would have an expected clearing time of no longer than two hours based on previous studies and evacuation methods.

Software Selection

Traffic simulation provides an effective method to analyze traffic data and implement strategies. For this study, the microsimulation software platform Aimsun 6.0 was chosen because of its ability to simultaneously run microscopic and mesoscopic simulation within one network. Another benefit is that Aimsun 6.0

is programmed with advanced features that generate certain traffic phenomena. One of these features is dynamic traffic assignment (DTA), which allows for two different schemes for both microscopic and mesoscopic simulation. The first is "a discrete choice model in which drivers take the cheapest path subject to a statistical distribution which can be one of three available by default (logit, c-logit, or proportional) or be defined by the user through Aimsun's powerful function editor." The second is a "Dynamic User Equilibrium scheme in which drivers select routes in accordance with a generalized equilibrium principle" (Aimsun 2008). This advanced feature creates a more accurate and realistic replication of the case study area. According to the Federal Highway Administration (FHWA), "a significant advantage of Aimsun 6.0 is that the gap-acceptance behavior of drivers is modified based on their delay time. Most other models do not represent such phenomena" (FHWA 2008). Aimsun 6.0 also offers existing post-processing analysis tools, which can be set to output data automatically after simulation. This is an advantage that other popular micro-simulation tools such as CORSIM, VISSIM, and SIMTRAFFIC lack. It is clear that Aimsun 6.0 can manage most of the typical behavior modeling characteristics.

Network Information

To make the results more accurate, a traffic network with fundamental details must be considered and input (Sterzin and Akiva 2004). To make the two-dimensional network as realistic as possible, the background of the Washington, D.C case study area was constructed by compiling images taken using the publicly-available tool Google Earth. The geometric design of the road network created in Aimsun 6.0 was then laid over the pictures drawn, closely following the imagery obtained from Google Earth. Due to the lack of actual data at the present time, the traffic control systems as well as the placement of traffic signals were designed based on assumptions. With the recent advancement in technology via Street View, another publicly available tool provided by Google, the placements of traffic lights have become more accurate.

Emergency Evacuation Strategies

To study the effectiveness of having public transit assisting the emergency evacuation, several evacuation safe zones (destinations) were placed in the network. The safe zones were placed outside a minimum one-mile radius around Union Station. They were also carefully selected based on ease of access from the emergency area.

According to Chang (2003), emergency evacuation modeling serves three main purposes: 1) pre-planning analysis, 2) real-time operation, and 3) post-planning procedure. All three are considered important for this study. The purpose of pre-planning analysis is to identify emergency evacuation routes that maximize efficiency. A major benefit of real-time operation is the ability to continuously update the traffic network to current conditions. The results from a simulation of real-time conditions can be used to evaluate safer and more efficient evacuation routes. Post-planning procedure involve the use of the output to evaluate evacuation operations.

Several emergency evacuation strategies were assessed in the proposed model to optimize the evacuation and emergency transportation responses in case of a terrorist attack at Union Station. Changing of signal timing is a roadway network strategy that has been applied to facilitate outward movement and reduce congestion on the main thoroughfare. According to the Regional Emergency Evacuation Transportation Coordination (REETC) Annex, it may be advisable to coordinate signal timing on key routes across jurisdictional boundaries by granting longer green time on the main thoroughfare and less green time to side streets in regional evacuation and emergency transportation responses (Metropolitan Washington Council of Governments 2004).

Evacuation Methodology

Many people who use public transit are often commuters from other areas. Thus, many people at a transit station during an incident will not have their own means of transport to a safe area. For this study, it was assumed that allowing people to self-evacuate a building will reduce panic and allow for a more effective procedure. Public buses will then be used to evacuate pedestrians to another Metro station or to safe zones that are located a secure, appropriate distance away. Once persons are out of a building, they would be instructed to proceed to existing bus stops to be transported to a predetermined safe area. For this case study, pedestrians would be evacuated by bus from Union Station to the Chinatown Station (approximately 1 mile away) and other safe zones (outside approximately the same radius). Pedestrians in good health also would have the option to walk to a safe zone. Since a person can walk a mile (safe distance) in about 20 minutes, allowing evacuees this option reduces the number of people in queue for evacuation buses and decreases the total evacuation time.

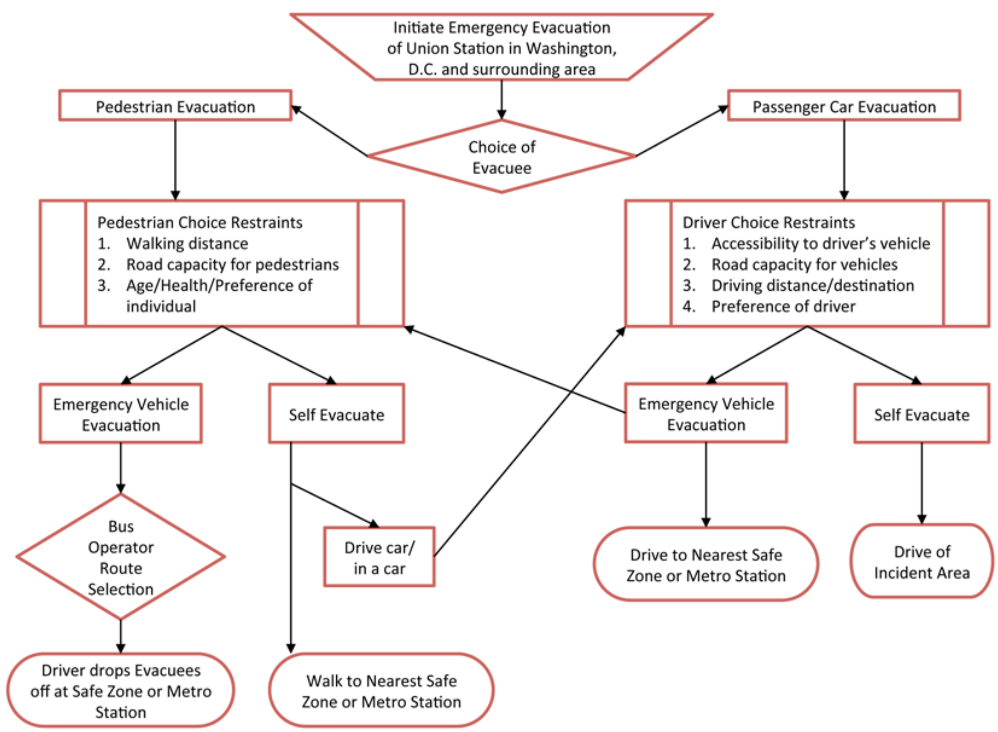
To plan for the best possible method of evacuating a large number of people from one Metro station to another, several strategies were tested by simulation. It was assumed that cars existing in the network would be cleared within 20 minutes after the attack until the evacuation strategies are implemented. This is important as there is a limited number of cars in the evacuation network during the Metro station evacuation.

The current evacuation plan for Union Station evacuates an estimated 70,000 people living, working, and passing through the area in 2 hours or less (CAPE-VAC is 70 minutes) (Liu, Chang, and Lai 2008). This time frame was used as the maximum allowable time for evacuation because the goal is to minimize evacuation time. However, because of the difference of time of day and severity of the incident, only about 25,000 people would need to be evacuated.

Figure 2-1 shows the individual decisions made by evacuees during the evacuation. After the initiation of the emergency evacuation of Union Station, evacuees would have the choice of evacuating by foot or by passenger vehicle. Pedestrian evacuees are constrained by the distance they must walk to reach a safe area, the road capacity for pedestrians, age, health, and preference of the individual. The pedestrian then has the choice of self-evacuating by walking to the nearest safe zone or Metro station or deciding to evacuate by vehicle. In instances in which the pedestrian decides to use public transportation to evacuate the area, he/she would walk to a bus stop, be picked up by the bus driver, and then be relocated to a safe zone or alternate Metro station. In instances of an individual evacuating the area by car, the driver is restrained by the accessibility to the vehicle, road capacity for vehicles, driving distance of the destination, and the driver's personal preferences. The individual would decide whether it is more feasible to self-evacuate using public transportation or a personal vehicle. In instances in which the individual decides to drive his/her own vehicle, the driver enters the road network and drives outside of the incident area.

Figure 2-1

Framework of Evacuation Procedure



Several strategies were considered for this specific case, including contraflow and corridor-based evacuation. The main goal of the situation was to minimize evacuation time with as little change to the traffic network as possible. Approaches such as contraflow and corridor-based evacuation were eliminated because they require far too much police assistance and setup to be practical for this proposed incident. As a result, a method of staged evacuation with the incorporation of public buses to evacuate pedestrians or people without vehicles was chosen.

To implement the suggested method of evacuation, Aimsun 6.0 was used to model and optimize the affected network. Origin-destination (O-D) matrices were placed in each traffic analysis zone (TAZ) and optimized to yield the most efficient paths for cars to follow while still considering driver choice using a combination of probability models and DTA. This simulation software also allowed for the utilization of public buses during an evacuation to be modeled. This plan requires that some buses within the network temporarily suspend their routes to assist in the emergency evacuation of the station. This was modeled using existing bus stops outside the station where evacuees can congregate and buses can arrive at a rate of every 5–10 minutes to carry a maximum of 40 passengers to either the adjacent Metro station or Chinatown Station or be taken to a safe zone.

Results

Pedestrian and Bus Evacuation

As previously stated, the majority of people being evacuated from the impact area at Union Station will not have access to a vehicle. An assumed 20–22 percent will choose to drive to a safe area, 63–65 percent will choose to walk about a mile to China Town station or another safe zone, and the remaining 15–17 percent (approx. 4,000 people) will wait for evacuation buses. This assumption was based on accounting for people with special needs (such as older adults or persons with disabilities), people who are unfamiliar with the area, and others who would prefer not to walk. Public buses in the area (coded in network) will temporarily suspend their routes and start arriving at designated bus stops to move people to safe zones. There are 29 available buses to assist in the evacuation.

After the network was simulated several times with different configurations of route choice, the optimum scenario was chosen and further evaluated using Aimsun. The optimum scenario was simulated for two hours and replicated several times. Some of the pertinent information from network simulation, automatically output by the program, can be seen in Table 2-1. The results for the following parameters are based on the number of buses available, their location at time of the incident, and the road conditions.

Table 2-1

Pedestrian/Bus Evacuation Scenario Averages

Number of available buses	29
Number of total bus trips necessary	96 combined trips
Trips per bus	3.4
Evacuation bus trip	15.9 minutes
Total evacuation time	54.1 minutes

As seen in Table 2-1, there are 29 buses in the simulation that have different initial arrival times due to the fact that they must first suspend their routes and head to the station. To evacuate the people at the station, it was determined that 96 bus trips are required to deliver all evacuees to safe zones. Aimsun 6.0 also determined that it took an average of 15.9 minutes for a bus being used for emergency evacuation to make a complete trip (from pick-up to drop-off and back to a bus stop).

Passenger Car Evacuation

During an emergency evacuation, it is important to take into account the immediate surroundings that include residential and commercial areas. Depending on the severity of the proposed attack on Union Station, the residential and commercial area immediately surrounding the station must be evacuated. Using TAZ data, it was estimated that there are approximately 5,500 passenger cars that would need to be evacuated. Using and optimizing O-D matrices with Aimsun 6.0, where origins are placed in the TAZs in need of evacuation and destinations placed in safe zones, results are shown in Table 2-2.

Table 2-2

Passenger Car Evacuation Scenario Averages

Number of cars to be evacuated	5,500
Evacuation time per car	7.8 minutes/car
Driving distance per car	3.4 miles/car
Total evacuation time	3.4 miles/car

Integrated Evacuation

The integrated evacuation was simply a simultaneous combination of the two scenarios optimized for the case study of Union Station and simulated in Aimsun 6.0. The entire evacuation of the network took approximately 64 minutes, as seen in Table 2-3, based on information obtained from evaluating the proposed emergency scenario.

Table 2-3

Integrated Evacuation Scenario Averages

Pedestrian/bus evacuation	54.1 minutes
Passenger car evacuation	63.3 minutes
Total evacuation time for combined modes	64 minutes

SECTION 3

Case Study 2: Emergency Evacuation Planning Model for Special Needs Populations Using Public Transportation

Background Information

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 is concentrated in these areas, especially during workdays, creating a vulnerable target for terrorists. These highly concentrated populated areas can lead to a high casualty rates if they are not evacuated quickly. Road networks become fully saturated in evacuation scenarios due to a large number of vehicles vacating; using public transit is one possible alternative to improve the level of service during evacuation procedures.

Employing different modes of transportation and aid from nearby jurisdictions have proven to be very effective in evacuation procedures. For instance, on 9/11 in New York City, "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…." (TRB 2008). Other than just using PATH trains 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 multi-modal evacuation and aid from New Jersey's public transit system proved that implementation of multi-mode transit resources can be crucial in emergency evacuation.

In Washington, D.C., the use of Metrorail proved to play a vital role in the September 11 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. City officials decided to keep Metrorail running in order to help evacuate the city. With Metrorail operating, the city was evacuated within 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 know if they are required to provide services during evacuations and, if so, the location of evacuation bus stops and routes. In the case of Hurricane Katrina, the public transit system was not fully used, leaving many citizens behind to weather the storm and the horrific recovery days following. The City of New Orleans had a plan that incorporated the use of school buses but did not designate who was responsible for using the buses 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 needs populations in the time of an emergency evacuation.

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

- Evacuating a larger number of people per trip
- Fewer personal vehicles clogging roadways
- Minimizing fuel usage for buses along evacuation routes instead of using fuel for numerous personal vehicles
- Professional drivers in contact with command centers and officials
- Accommodating special needs populations

Mastrogiannidou et al. (2009) found that 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. 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 operating during special events such as concerts, sporting events, and other dealings that draw large crowds (Scanlon 2003).

Problem Statement

The main goal of this research was to evaluate different evacuation procedures for special needs populations from large urban areas in a time of a no-warning emergency using current public transit systems. For the purpose of the study, special needs populations include, but are not limited to, people with physical disabilities, older adults, non-English speaking populations, residents and employees without vehicles, and tourists. The specific objectives completed 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 who engage in its transportation services. Being in the heart of the downtown core of the District, many workers are employed near the station. In addition, it is within walking distance of 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 used 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 were assessed. Emergency evacuations are becoming more commonplace, and metropolitan planning organizations and transportation engineers are assessing these new planning requirements, especially in the case of our nation's capital.

Case Study Area

For this study, the downtown core area of Washington, D.C. was chosen to be analyzed. In Figure 3-1, it can be seen that the District of Columbia has boarders that resemble a diamond shape, except for the west side of the District where the border 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 include the large diverse urban population, important government buildings, a complicated road network, and a significantly large population that depends on public transportation. As reported by the U.S. Census Bureau, the District of Columbia had a population of 591,833 in the 2008. On weekdays, this figure can increase by 72 percent, with about 410,000 people entering the city for business purposes (Longley 2005).

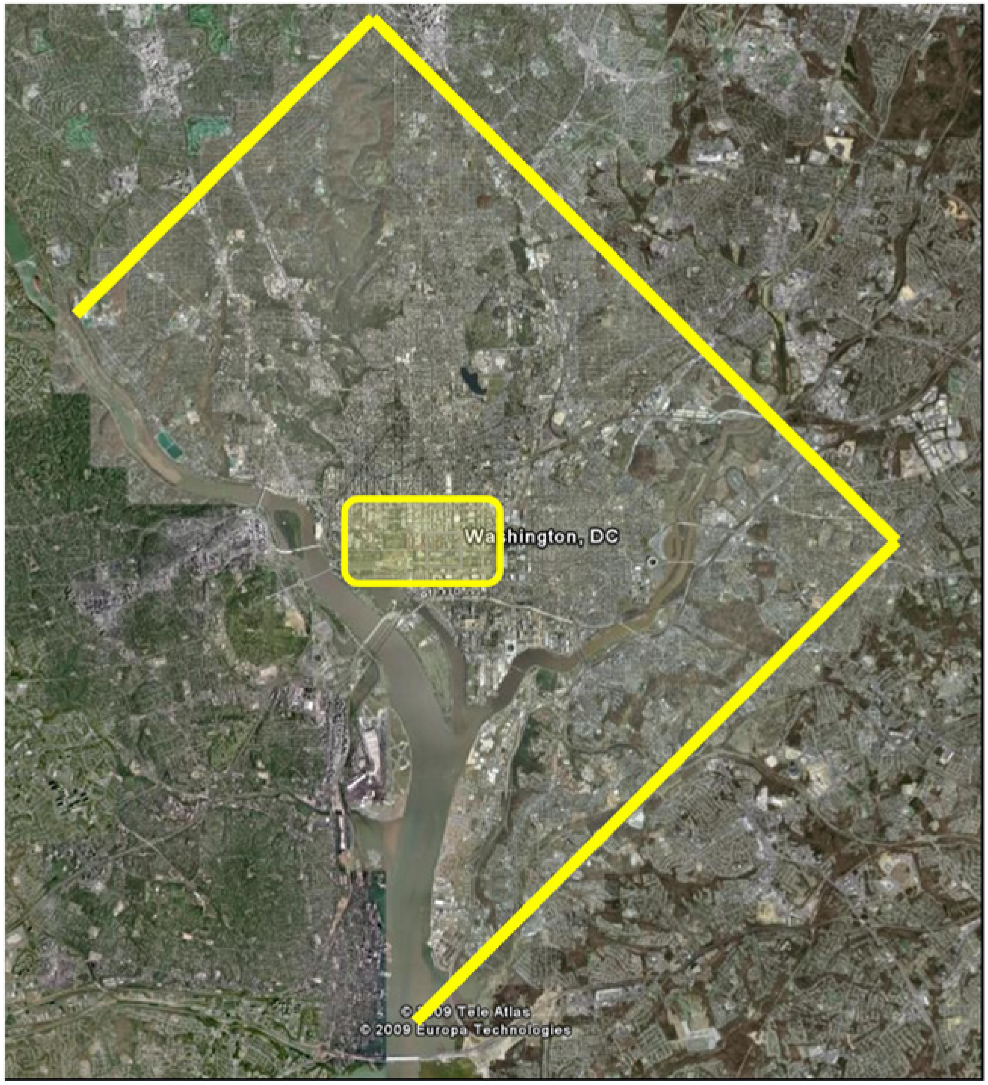


Figure 3-1

Case Study Area: Washington, D.C.

Source: Google Earth

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 U.S. president and other elected officials who hold great responsibility and decisionmaking positions for the nation. The headquarters of 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 include the Washington Monument, Smithsonian Museums, the Capitol building, Mount Vernon, the National Zoo, Old Town Alexandria, Dupont Circle, 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 passenger traffic of approximately 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 and extends far into 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 far beyond 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 quarter-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 into the city for business or pleasure purposes. If trying to make a statement, terrorists can surely get noticed by conducting an attack on the nation's capital.

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 comprises Metrobus, Metrorail, and the newly-added MetroAccess. Metrorail service has 106 miles of track and 86 stations throughout the Washington, D.C. area. The Metrorail 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 includes 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 operation in 1994.

The service area of Metrobus and Metrorail is approximately 1,500 square miles and serves about 3.4 million people. WMATA operates the second largest metro rail system in the United States and the sixth largest bus network. In fiscal year 2009, Metrorail and Metrobus had a combined total of 356.7 million trips. Metrorail services the areas of Washington, D.C., suburbs in Montgomery and Prince George in Maryland, and suburbs of Alexandria, Arlington, and Fairfax County in Virginia. A majority of employees that work in the downtown core of Washington, D.C. use Metrorail and Metrobus services to get to work from nearby suburban 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 is shown in Figure 3-2.

Figure 3-2

Metrorail Map of Washington, D.C

Source: WMATA, 2009

Another public transportation mode that serves the city is the Metrobus system. The entire service area includes 319 routes on 174 lines, with a total of 12,227 bus stops; WMATA owns and operates 597. The buses used by WMATA have the capacity to seat an average of 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 accessible to persons with disabilities. Priority seating directly behind the driver is provided for older adults and people with disabilities. Currently, about 70 percent of the buses owned by WMATA have audio stop broadcasts and digital visual text signs that announce major transfer intersections and stops.

WMATA recently opened a new transportation division called MetroAccess that caters particularly to passengers with physical disabilities. This sector of WMATA provides door-to-door paratransit service to passengers whose disabilities prevent them from using regular bus or rail services. Customers need to meet requirements set by WMATA 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.

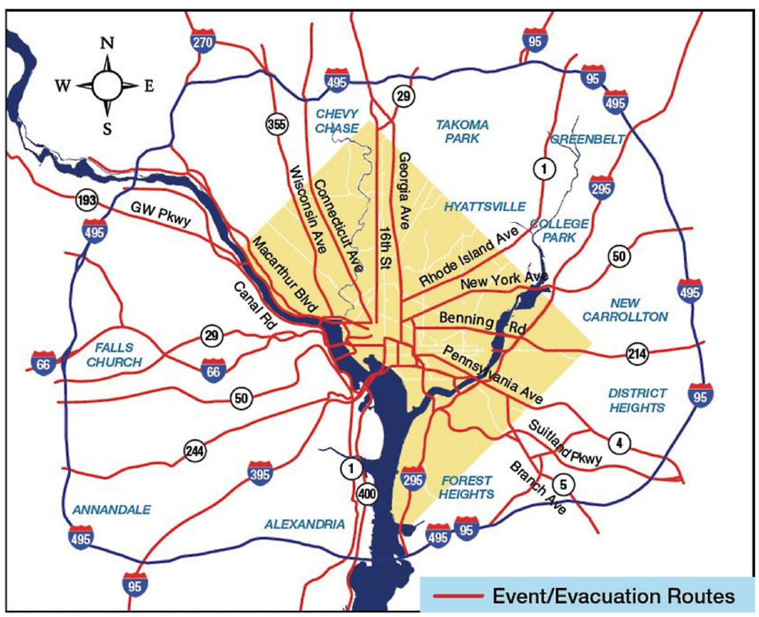
Washington, D.C. Current Evacuation Plans

Current evacuation plans for Washington, D.C. are composed of 19 major corridors exiting the city leading to the Capital Beltway, I-495. Secondary route choices have also been designated by the District Department of Transportation (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 3-3.

Pennsylvania Ave. (which runs diagonal through downtown from northwest to southeast) is designed to act as a dividing line for the direction in which 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 the roadway.

Figure 3-3

Evacuation Routes for District of Columbia



Source: DDOT, 2002

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 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).

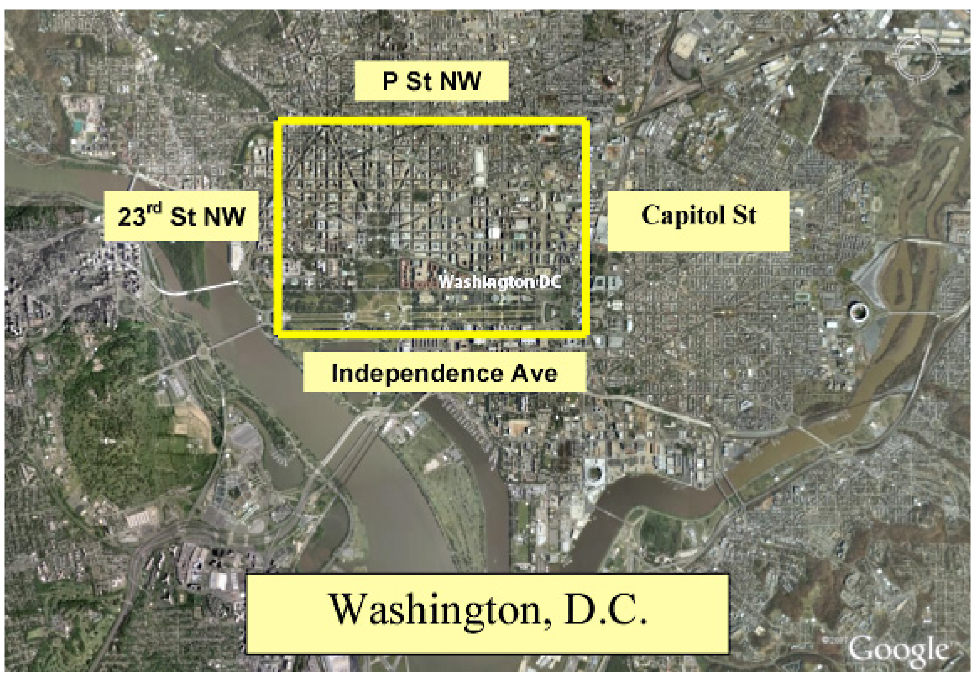
The District has also prepared for the complete shutdown of Metrorail in case operations are disrupted or if shutdown is needed for safety in case of an emergency. According to the District Response Plan, the loss of Metrorail "would be catastrophic for the transportation system … and will need to be 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 non-residents without vehicles to explore other transportation options, such as carpooling, taxi, and walking.

Road Network

A microscopic simulation model of Washington, D.C. core downtown area was constructed in the simulation platform Aimsun 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 3-4. It incorporates 62 TAZs 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 DDOT.

Figure 3-4

Extent and Boundaries of Case Study Area for Road Network



Source: Google Earth

The network comprises 129 miles of road and 621 intersections and has approximate dimensions of 2.8 x 2 miles. In this document, "node" is used to define all intersections and merges, and "centroid" is used to refer to O-D or safe-zone centroids. The average lane width of all roads generated within the network was 12.1 feet.

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 7–9am. Midday off-peak and PM peak period signal timings represent the hours of operation from 10am–2pm and 3–7pm, 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 O-D matrices and validated using 2006 traffic counts from the DDOT. These everyday O-D matrices were received from the agency under the Metropolitan Washington Council of Governments (MWCOG) and the National Capital Region Transportation Planning Board (TPB). The everyday matrices were used to produce background traffic on the model before the evacuation commenced and validated the model when compared to traffic counts. The O-D matrices were given in the computer software package Cube Voyager. The entire trip table matrices of the entire Washington metropolitan consisted of 2,191 rows and 2,191 columns to represent all 2,191 TAZ located within the Washington Metropolitan area.

Each O-D matrix provided from the TPB was categorized based on mode. A total of five different modes made up the entire everyday traffic demand. The first three tables were combined to find the total trips of cars in the network. The five trip tables were categorized as the following:

- SOV vehicles
- HOV 2 occupancy vehicles
- HOV 3+ occupancy vehicles
- Medium trucks – 2 axles, 6+ tires
- Heavy trucks – all combination vehicles

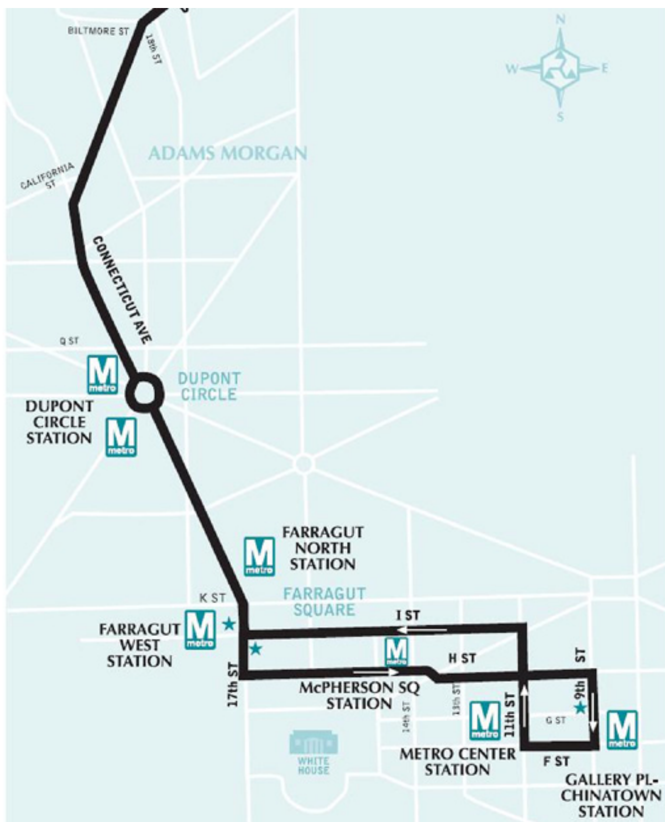
The travel demand for the evacuation traffic of the network was found by using demographics provided by the U.S. Census Bureau. Demographic records organized by TAZ were analyzed and manipulated to calculate the number of vehicles, pedestrians, and special needs populations that would need to be evacuated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

To enter the O-D matrices, the production/attraction centroids for each TAZ 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 O-D matrix to be used to produce 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; more than 40 different bus routes operate within the case study area. Each route was entered into the network with all corresponding bus stops and timetables for the time interval of the simulation run. One notable route is bus route 80, which 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 3-53-5 and has several stops at Metrorail stations. Routes 13A, 13B, 23F, and 13G all circulate around the National Mall, providing tourists with a means of travel to surrounding areas.

Figure 3-5

WMATA Bus Route 42



Source: WMATA, 2007

Simulation Platform

The 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 analyses are more sound (Barcelo and Casas 2002). Simulation models are able to supply an 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 6.0 Professional.

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 6.0 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 6.0 User's 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 on a large set of algorithms that range from headway to dynamic user equilibrium.

Evacuation Scenarios

Terrorists conceal multiple bombs throughout the downtown area of Washington, D.C. According to Noh et al. (2009), at approximately 11:00 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 Place/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 needs 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 needs populations to evacuate and will require the same number of evacuation bus trips. The evacuation bus routes will follow normal operations to the bus stop locations. After a bus is loaded with evacuees, it will continue along the route until it reaches an evacuation corridor. The bus will then proceed to the nearest safe zone using the pre-set evacuation corridors.

Methodology

To develop methodologies to deploy public transit vehicles to better incorporate special needs populations and adhere to current evacuation plans set for Washington, D.C., different scenarios were 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 evacuating. Using bus routes and bus stops currently in place for the case study area, the best scenario was found to evacuate special needs populations. The following section covers the production of trip generation and trip distribution, the bus stop location optimization model, and the simulation methodology.

Origin-Destination Matrices

Considering the large size and specific demographics of special needs populations located within the boundaries of the microscopic simulation network, O-D 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, whereas an O-D 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 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, 71 centroids are used to represent origins and destinations—62 centroids for each TAZ and 9 centroids for the 9 safe zones.

The configuration for an O-D centroid for TAZs 33, 29, 24, and 34 is shown in Figure 3-6. The simulation software has the capability of storing several different trip matrices using the same set of centroids located within the model.

Figure 3-6

O-D Centroids Found in Aimsun Network

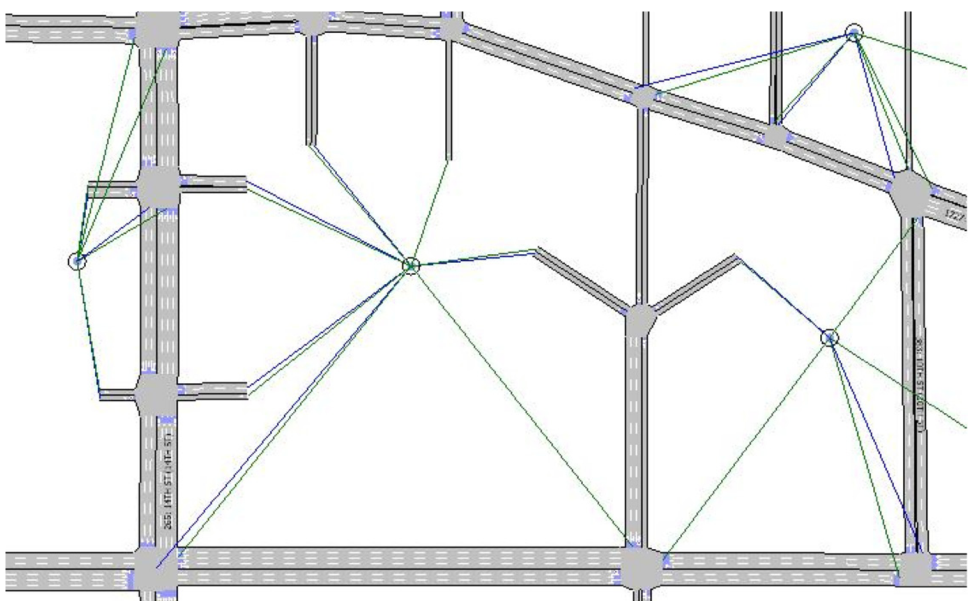


Table 3-1 Illustrates a small portion of the everyday car trip matrix for TAZs 1 through 5. The same O-D centroids were used for the evacuation trip matrices.

Table 3-1

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

Background Traffic Demand and Assignment

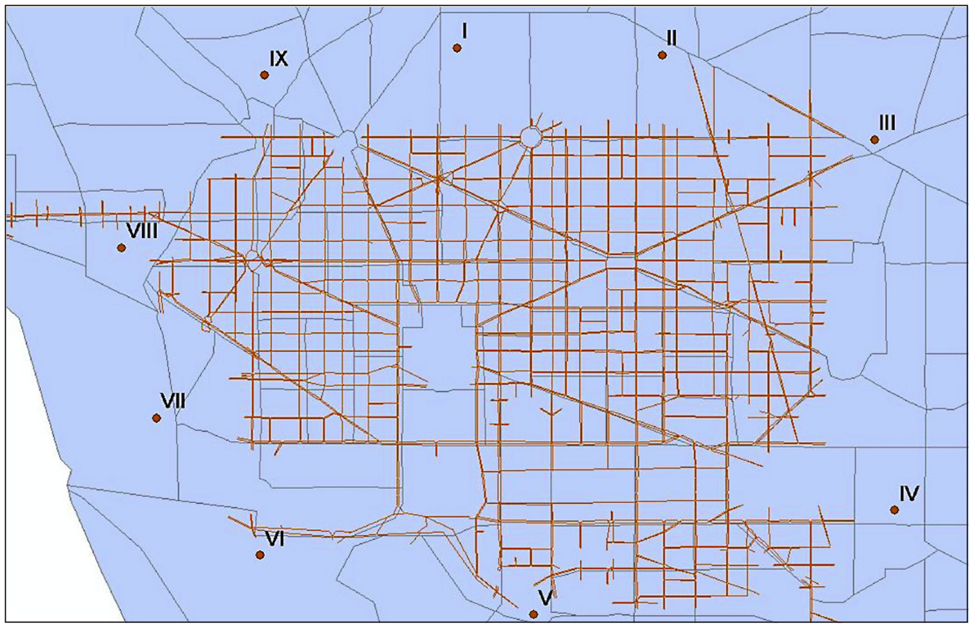
The everyday trip matrices received from MWCOG had to be manipulated to be compatible with the downtown core Washington, D.C. network constructed for this analysis. The given matrices from the transportation planning organization were composed of 2,191 TAZs that included the entire metropolitan area of Washington, D.C. and extended 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 into the background traffic. A method was devised to include these outer zones in the smaller dimension O-D matrix to be used within this research's simulation model.

As stated previously, the model used for this study employs one O-D centroid for each traffic analysis and safe zone. The safe zones are used to represent a safe location that is a safe distance from the hazardous area and that is 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, the Red Cross, or FEMA) until recovery can begin, and they are no longer represented in the model. To keep the simulation close to real-life conditions, current evacuation routes were used to lead vehicles to safe zones. Therefore, the nine 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 3-7. Only one safe-zone centroid was 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 were 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 (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.

The centroids corresponding to safe zones generated in the simulation model have two purposes. First, they are used to represent the safe area that is 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 contain only pure attractiveness for vehicle trips. Second, they are used to represent the trips originating from and destined to and from locations outside of the computer model for the everyday background traffic. As mentioned previously, the O-D matrices provided by the MPO included trips from zones located outside the computer road network but still necessary 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.

Figure 3-7

Safe-Zone Centroid Configurations

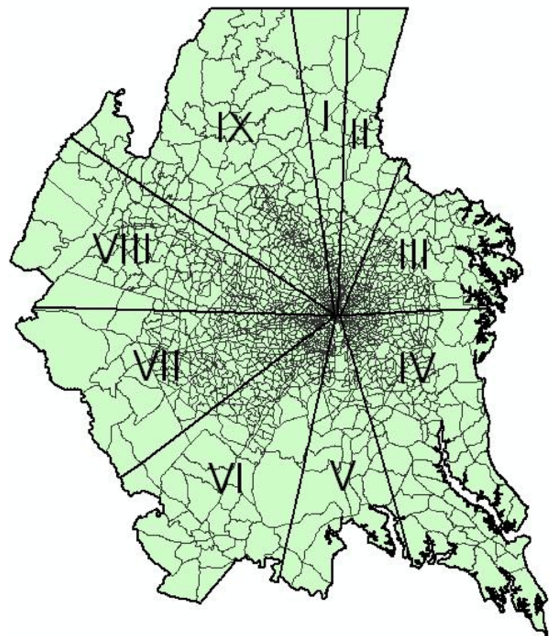


Two O-D matrices fabricated from six sections were used to accurately represent the everyday background traffic of Washington, D.C. in the simulation platform. The matrices were formed using the same information the local TPB and MPOs use for traffic forecasting of the area. One matrix represents the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

The second and third set of trip matrices represent the everyday background traffic of cars and trucks that are either traveling out of or into the computer network built for this analysis. For simplicity, to model these trips within the simulation network, the exterior TAZs were grouped together into nine separate sections and are delineated by the safe-zone centroids. To combine the remaining 2,129 zones not occupying the virtual network, the Thiessen Polygon Method was used. 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 used 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 is used to represent all the trips produced by 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 3-8).

Figure 3-8

Thiessen Polygon Distribution of Outer TAZs



Several traffic analysis zones were divided between two safe-zone polygons. To accurately determine the number 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 3-9 and Equations 1–3 in the Appendix). 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.

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 need to be taken in to account to obtain an accurate number of evacuees. Statistics such as

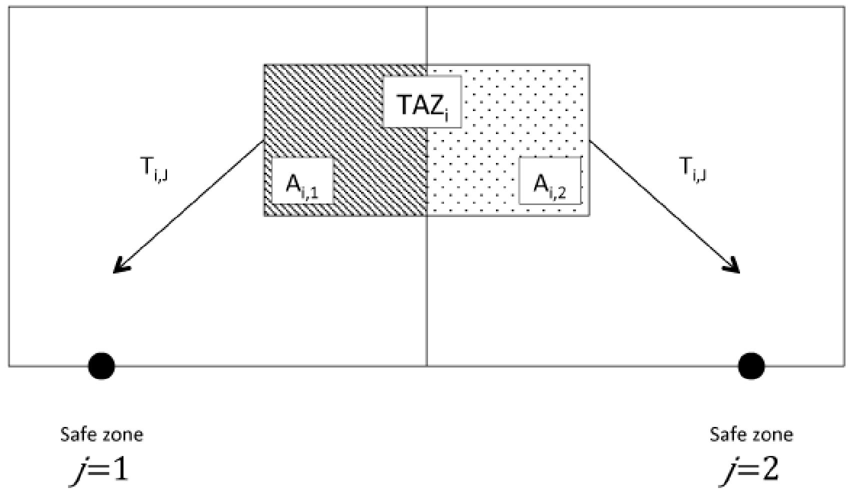


Figure 3-9

Area-based Method to Develop New Vehicle Trips from Divided TAZs

the number of employees, residents, and tourists located in each TAZ at the time of evacuation were used to produce the traffic production of each zone.

The first step in developing the evacuation O-D matrices required obtaining the trip production for each TAZ. Using demographics obtained from the U.S. Census Bureau, trip production for personal vehicles in each TAZ was calculated by Equations 4–6 in the Appendix.

According to U.S. Census, the unemployment rate for Washington, D.C. is approximately 9 percent. 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 number of employees and tourists located in the same zone. Using Equation 4 from the Appendix, 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 do not use public transit. Based on the MWCOG weekday planning model, about 36 percent of the population uses public transit services in the city. Equation 6 factors in the percent of the population that carpool to work in the city.

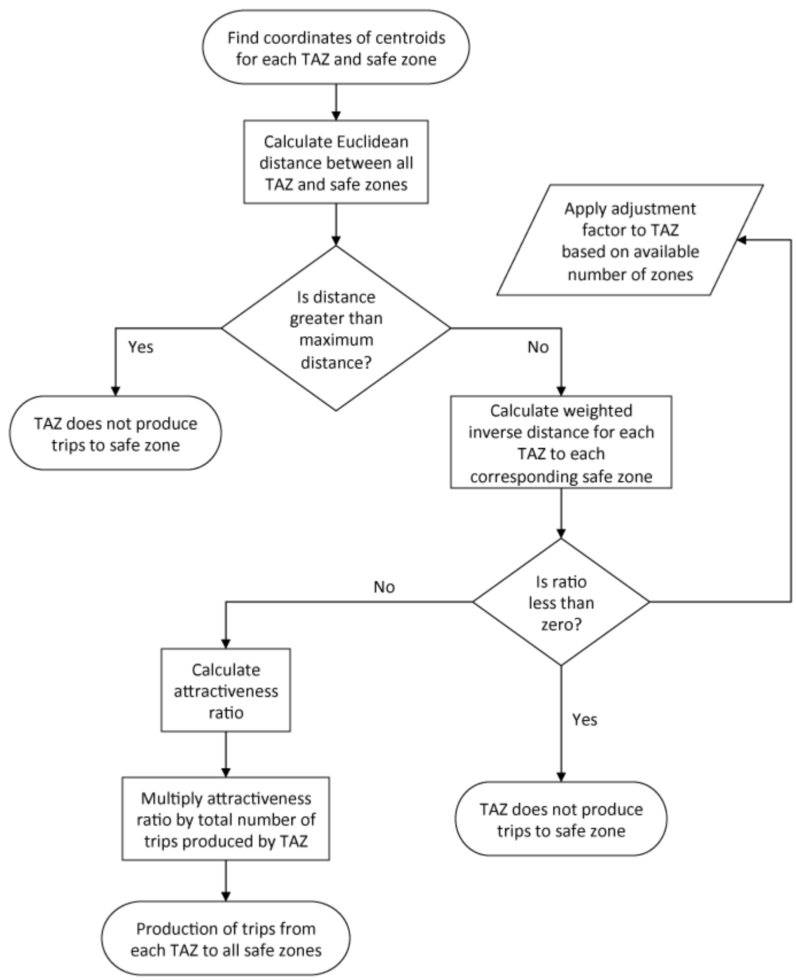
The number of people in each TAZ that rely on public transit for evacuation was obtained from further analysis of demographic data. To estimate the number of people without a vehicle, the total number of people using personal vehicles was subtracted from the total number of people located in that zone during the evacuation scenario. For this study, it was assumed that special needs populations that are able to drive themselves to work can also evacuate themselves in time of emergency. Moreover, using U.S. Census data, the number of persons with disabilities, older adults, 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 evacuate an area is a very complex procedure. In this analysis, the main focus was on the exit of public transit vehicles such as buses that have a set route for evacuation. To have the road network properly loaded with personal vehicles to simulate how well bus routes service special needs 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 7–14 in the Appendix.

The trip distribution procedure presented in the flowchart in Figure 3-10 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 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. Last, if the safe zone is an unreasonable distance away, it is safe to assume that drivers from that particular TAZ will not exit the system using the outlying safe zone.

Figure 3-10

Flowchart of Trip Distribution Procedure



Mathematical Model of Bus Stop Locations

The goal of this mathematical model was to maximize the overall benefit of evacuation bus stops located within the case study area using linear programming with binary variables. The objective function and constraints are presented in Equations 15–22 in the Appendix.

The goal of the objective function was to maximize the overall benefit of chosen evacuation bus stops. Binary variables ($\phi_{b,z}$) are decision variables within the optimization model, used 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 TAZ within the case study area (Equations 17, 18, 21, and 22). The total number of bus stop locations that can be selected for the area is set by Equation 19. The criteria for selecting evacuation bus stops are 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 its inverse distance to a given bus stop. However, for other groups of interest, such as special needs populations, the size of population (ρ) of each special needs group will introduce another factor to the benefit function. For instance, a bus stop located near a larger population of persons with disabilities will have a higher benefit than a lower population for the same given distance.

Depending on how far away an area of a special needs 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 0 was 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 was defined, so that the inverse distance was 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 needs population, still allowing for some benefit to be included. The effect of this distance factor can be represented by Figure 3-11, where range A corresponds to the baseline radius and range B corresponds to the relaxed radius.

The decision maker has the ability to express his/her preference towards a specific special needs group by defining its importance (ω). Weight assignment

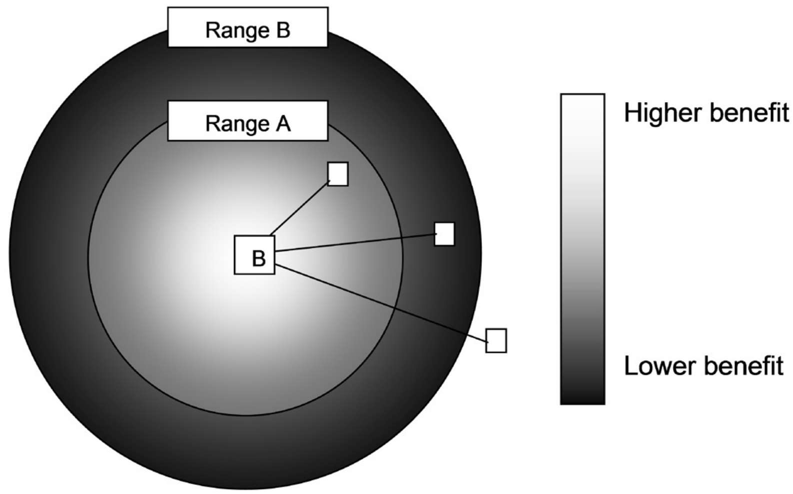


Figure 3-11

Radius-based Distance Factor

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 needs groups that would require extra assistance in evacuation. Eventually, special needs groups will demonstrate a certain correlation (i.e., low-income individuals not owning a vehicle), requiring the decision maker to evaluate the weight assignment 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 a 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 older adult populations and a much smaller weight to employees. Each geographic region is likely to contain different larger special needs populations that would require more assistance in an evacuation scenario, stressing the importance of 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 being clustered in one area that represents the greater benefit value in the whole study area. Equation 18 was introduced to inhibit a grouping of bus stops in each TAZ. By dividing the study area into 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 the 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 serve. That maximum number of trips (T^{max}) is then divided by the entire number of trips required for the zone, producing the number 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 is produced. The formulation then uses the larger of the two values to set equal to N_z^{max}. If the total number of trips needed and the area of a zone do not reach a set value (ξ), 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 (see Appendix for Equation 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_z^{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 TAZs 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 TAZs (z=10,11,12,13) have very small special needs 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.

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 one bus stop per section and a more even spatial 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.

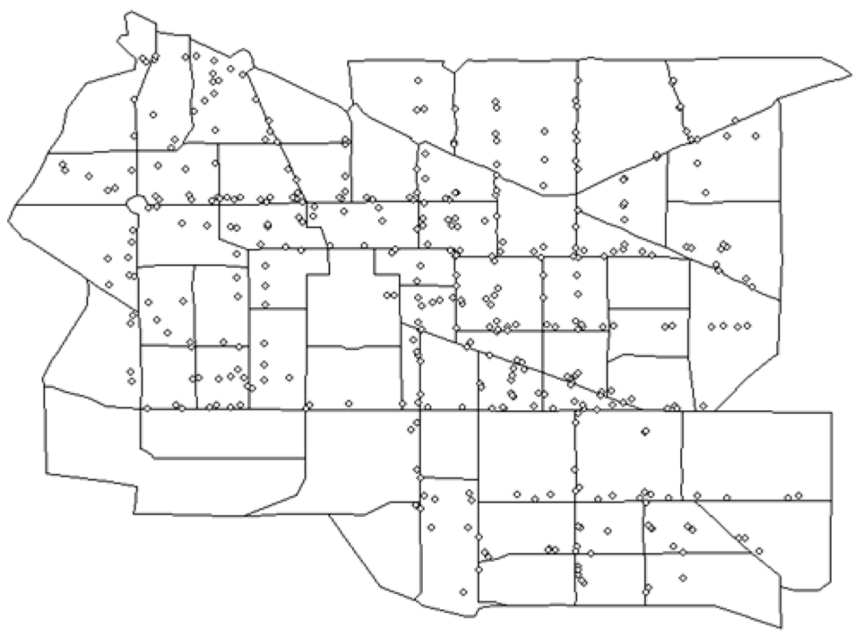
Application to Case Study Area

In this particular research, the goal is to maximize the benefit of chosen evacuation bus stop locations that would serve a greater number of special needs populations for the Washington, D.C. downtown area. The current number 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 shapefiles were then modified to include only the bus stops located 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 3-12 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.

Figure 3-12

Bus Stops within Case Study Area

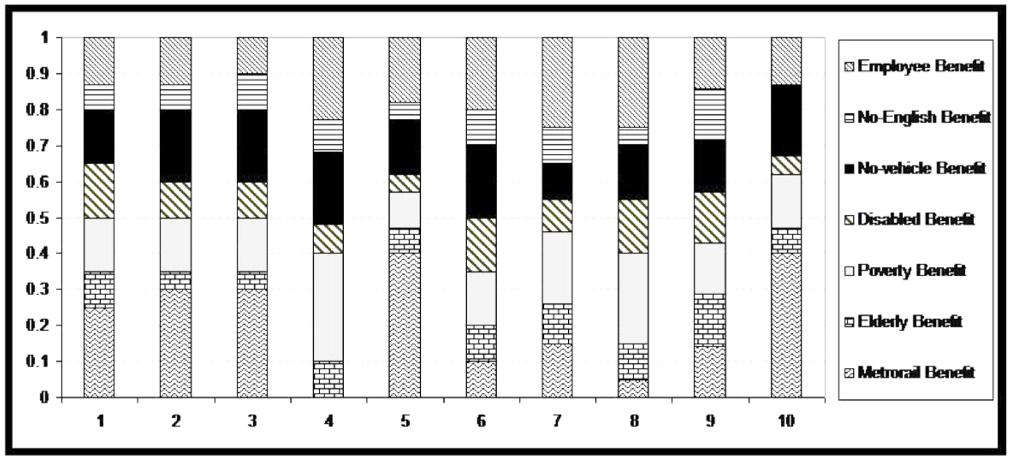


As stated earlier, N_z^{max} is a function of the trips required and area of a traffic analysis zone. A zone with a larger area requires more stops, as stated in Equation 21. This is to prevent an evacuee having to walk an unreasonable distance to a bus stop despite the fact that they are both located 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 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 provided the best results for this case study.

Originally, demographics for the case study area were collected by TAZ. It was soon noted that the TAZs grouped data into polygons that were too vague to determine precise locations of special needs populations. Bearing in mind that one TAZ could incorporate up to 12 individual bus stops, specific locations of special needs populations needed to be known. Consulting the U.S. Census Bureau for more detailed data, demographics were collected at the census block level. Census block data were collected for older adults, low-income individuals, non-English speaking individuals, and people with disabilities. Ten different weighting schemes were evaluated as a sensitivity analysis to account for different decision maker inputs (Figure 3-13).

Figure 3-13

Sensitivity Analysis Weighting Schemes



Once all inverse distances, population sizes, and distance factors were known, the benefits for each bus stop were used 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 3-14). The optimization formulation was solved using a linear programming solver, using the simplex method.

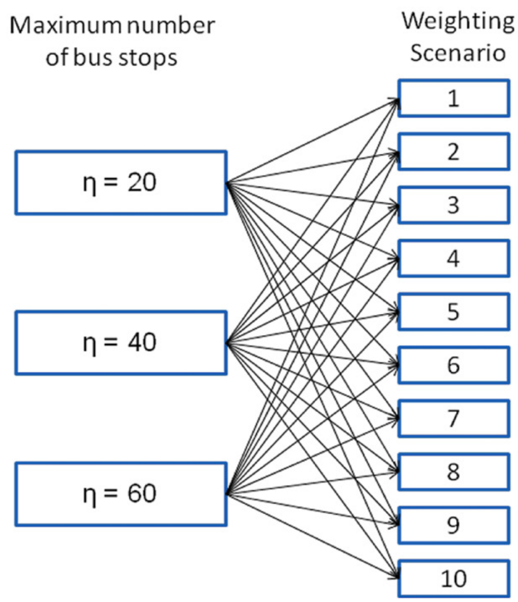
The selection of the weighting scheme to be used for the simulation portion of this research was based on probability. The weighting scenario that yielded the greatest count of bus stops within the most frequently chosen stops for all weighting scenarios was selected. It was assumed that if a bus stop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

Simulation Modeling

The microscopic platform Aimsun 6.0 was used 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 were simulated for each number of evacuation bus stops using a new random seed for each replication. An average was then established from all 10 replications.

Figure 3-14

Distribution of Optimization Model Scenarios



Network Calibration

To use 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 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; values closer to 1 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 an R^2 close to 1 is obtained, the network is successfully calibrated.

Simulation Scenarios

All simulation scenarios contain a certain amount of traffic input similarities. The personal vehicle evacuation traffic was loaded into the network in four-hour time intervals. The evacuation traffic was divided into four one-hour demands that arrived in the network exponentially. All needed bus trips will depart during this network loading time interval. Each origin centroid for each TAZ located within the network has established O-D routes that incorporate the corridor evacuation routes. Vehicles were assigned to follow O-D routes at 100 percent. A standard network clearance time of three hours was provided to clear gridlocked intersections and bottleneck sections and have the majority of traffic reach safe zones.

Each simulation scenario has to contain a required number of bus trips to effectively evacuate all the special needs populations within the case study area. For simplicity simulation purposes, the required number 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 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 contained only one stop. Therefore, one bus trip contained only one evacuation bus stop of 50 passengers. The bus routes represent current bus routes used within the case study area until the pickup location. Once the bus is full of passengers, the bus will proceed to the nearest corridor evacuation exit.

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 section.

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 the Thiessen Polygon Method to represent spatial data. Safe zones 4 and 9 produced the largest number of car trips entering the network from the zones located outside the network area (Figure 3-15). This number differs from the number of truck vehicle trips entering the network. The safe zone that produced the most truck trips entering the network is safe zone 3 and can be seen in Figure 3-16.

The vehicle trips exiting the network were also divided into the nine safe zones employing the Thiessen Polygon Method. The vehicle trips exiting the network favored the same safe zone centroids as the entering trips.

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 number of vehicle trips were produced in or 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.

Mathematical Model Results

The mathematical results yielded the total benefit of evacuation bus stops according to the weighting scheme and the maximum number of bus stop occurrences, both of which are dependent upon the decision maker's preferences.

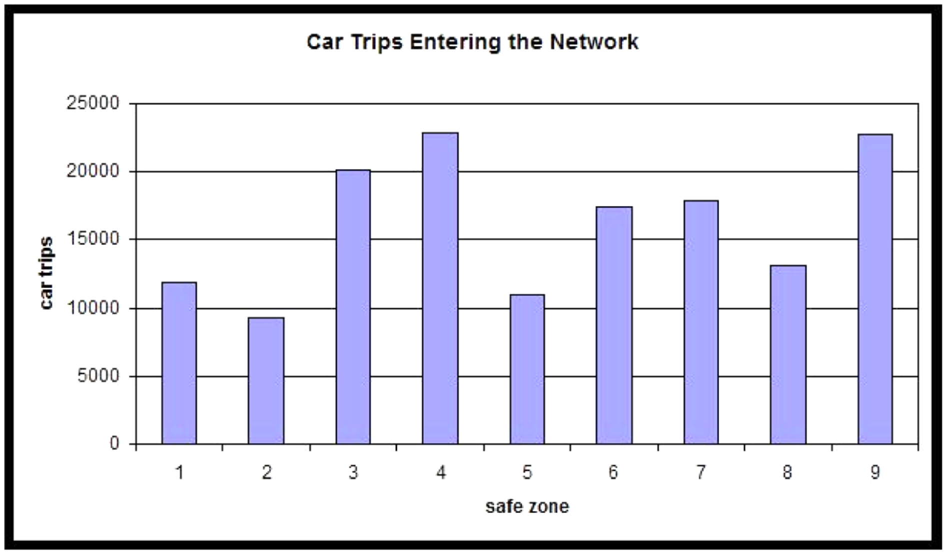


Figure 3-15
Cars Entering Network

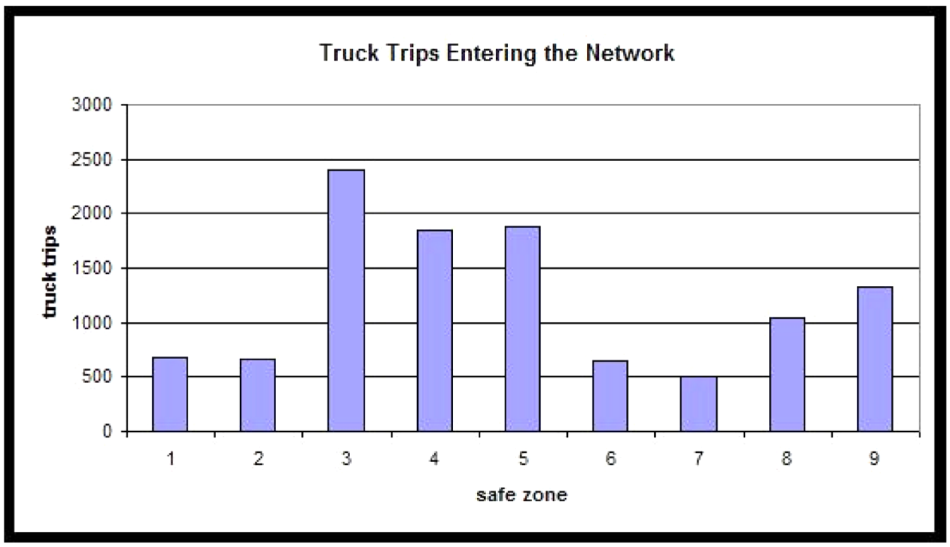


Figure 3-16
Trucks Entering Network

To find the results that would be best to simulate for the evacuation scenario, several step were taken.

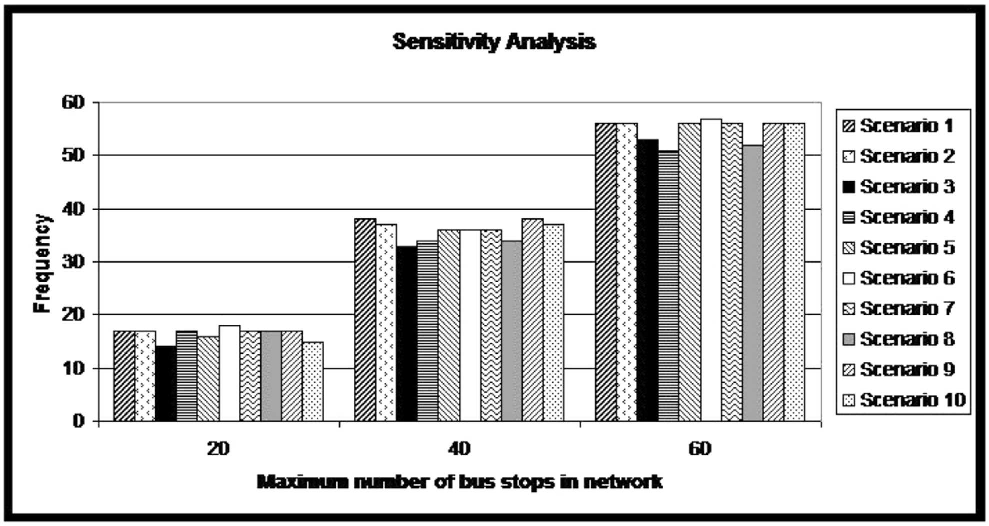
Sensitivity Analysis for Weighting Scheme Selection

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. Older adults and persons with disabilities might find it difficult to work and, as a result, would fall into the category of poor as well. Considering this relationship, an individual might be accounted for twice in the given optimization formulation for special needs populations. Therefore, a weighting scheme had to be developed to carefully account for all special needs 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 were based on percentages of total population, resulting on an inaccurate correlation very close to 1. A sensitivity analysis was performed 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 3-17). The scenario that most frequently selected the same bus stop locations for all 10 scenarios was then chosen for simulation purposes.

Figure 3-17

Sensitivity Analysis



In Table 3-2, it can be seen that that the bus stop location frequency among all 10 weighting scenarios are very close; however, in general, weighting scheme 6 had the most frequently selected bus stop locations ranked among the best-ranked for all 3 maximum number of bus stop scenarios. The frequency of selected bus stops is better represented in 3-2. 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 40-bus-stop scenario 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 among 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 needs populations.

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

Table 3-2

Bus Stop Frequency Organized by Bus Stop Scenarios

Scenario	Weighing Schemes									
	1	2	3	4	5	6	7	8	9	10
20	17	17	14	17	16	18	17	17	17	15
20	18	37	33	34	36	36	36	34	38	37
20	56	56	53	51	56	57	56	52	56	56

Table 3-3

Weighting Scenario 6

Scenario	Metrorail	Older Adults	Poverty	Disabled	No-Vehicle	Non-English	Employee
Weight	0.1	0.1	0.15	0.15	0.2	0.1	0.2

Bus Stop Clustering

The bus stop locations yielded from the optimization model proved to have the highest benefit for special needs 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 3-4. 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 3-4

Maximum Benefits of Trial 1

η	Total Benefits
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 3-18 indicates that the model delivered the three necessary bus stops surrounding the terrorist interest point, the Gallery Place/Chinatown Metro station, as a constraint was declared for that specific TAZ zone enforcing a minimum of three bus stops. These three 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 number of employees located in this region.

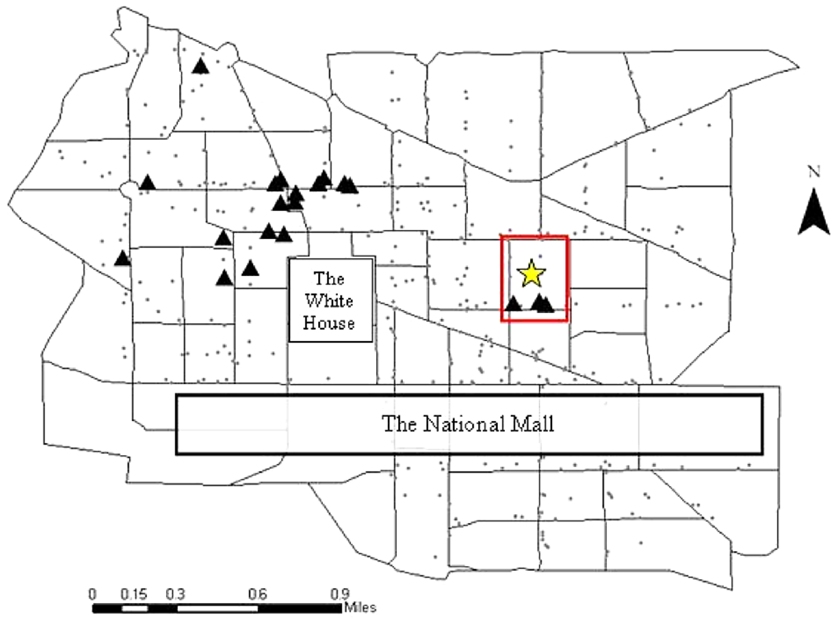


Figure 3-18

Optimum 20 Bus Stops from Trial 1

The total benefit found for the 20 bus stop locations represented in Table 3-4 was 42.88 and was one of the highest among all 10 of the weighting scenarios for the 20-bus-stop 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 located northwest 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 TAZs containing evacuation stops, leaving most of the zones 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 68.30. This is a likely result in that the more bus stops selected, the more benefits the objective function will contain to sum (Figure 3-19).

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 northeast 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 be located in this area, so extra constraints were added to the formulation to account for this area.

After adding another 20 bus stops, for a total number of 60 bus stops, the maximum total benefit increased to 79.32. Figure 3-20 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 3-19

Optimum 40 Bus Stops from Trial I

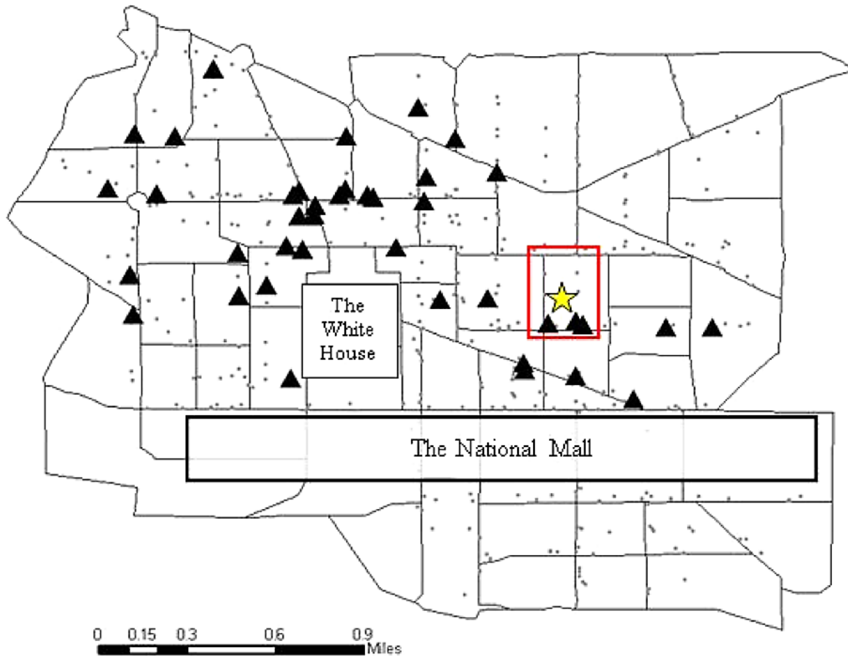
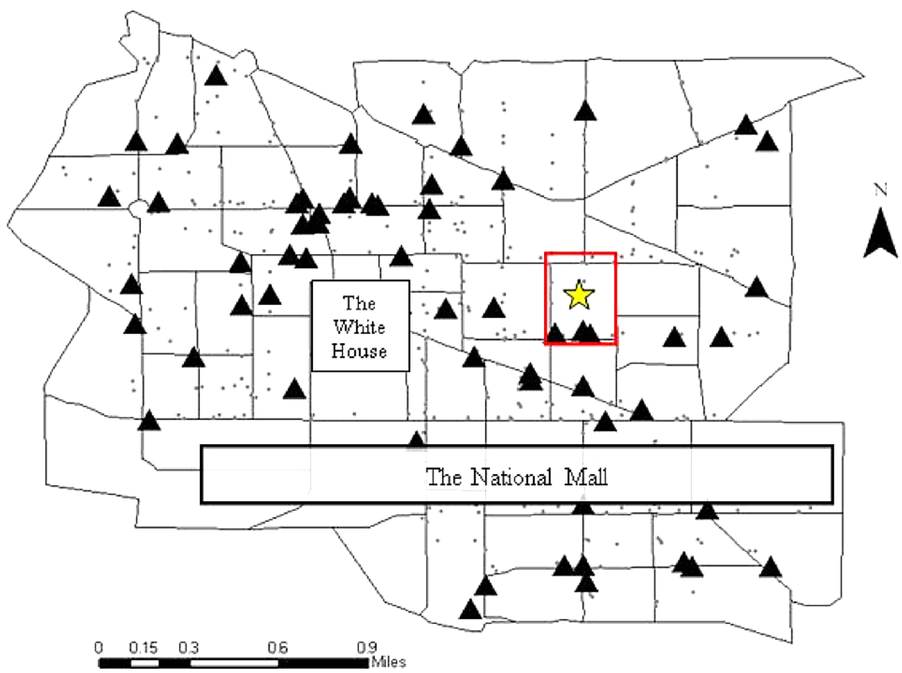


Figure 3-20

Optimum 60 Bus Stops from Trial I



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

In an actual evacuation, bus stop locations must be available for service throughout the entire network and not in just one concentrated area. Despite the fact 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 to serve all special needs populations throughout the entire downtown area to comply with practical evacuation planning.

Addition of Spatial Constraints

To obtain the number of evacuation bus stops that are more evenly spread throughout the case study area, a grouping of TAZs 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 3-21 illustrates the 3 x 3 grid implemented for this to prevent the clustering effect. Once the TAZs were grouped by the 9 grid sections, 9 new constraints were inserted into the formulation model.

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 bus stops. The total benefits can be seen in Table 3-5. 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.

Figure 3-21

Grid Grouping of TAZs

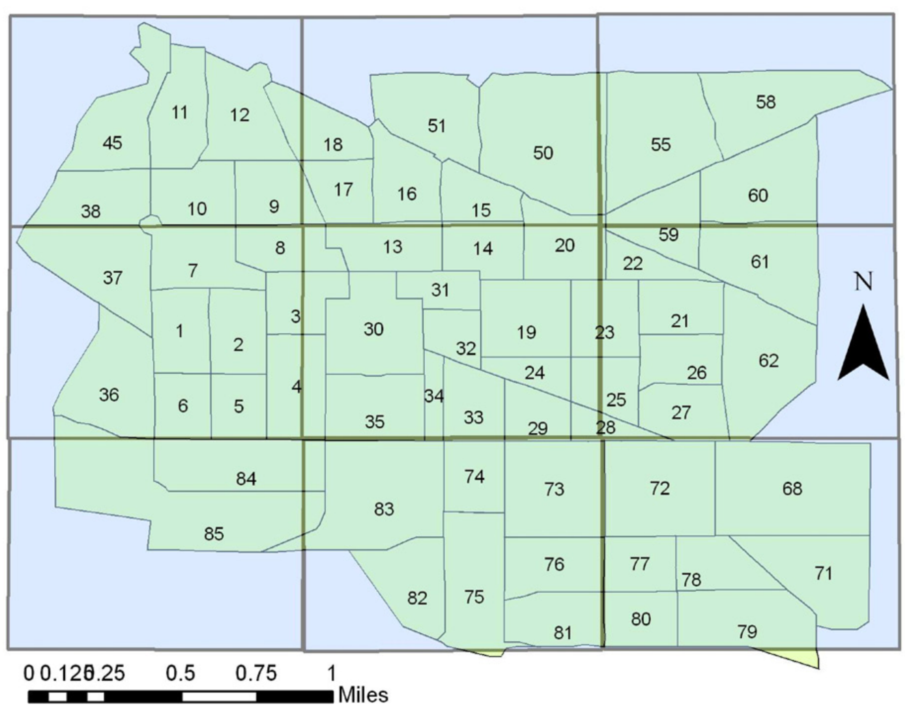


Table 3-5

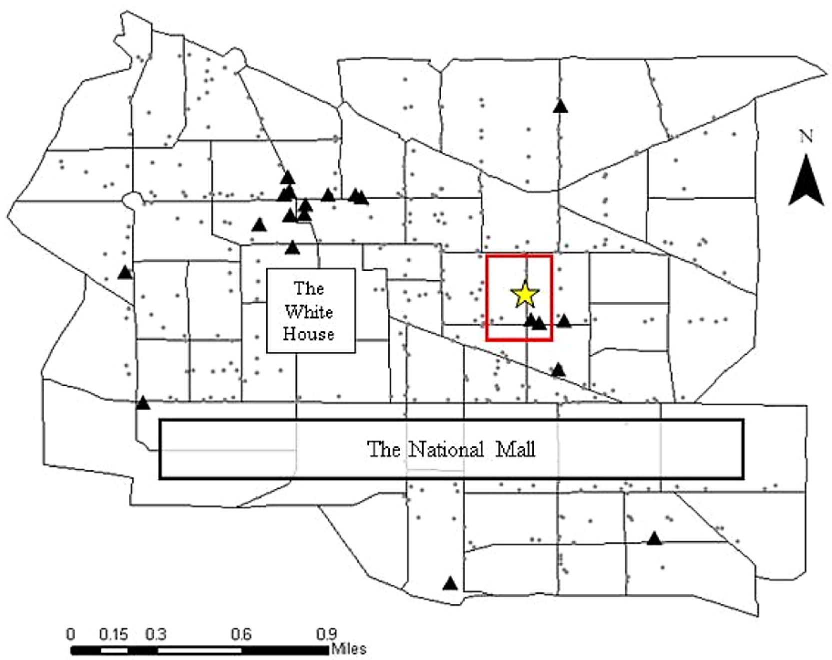
Grid Implementation Total Bus Stop Benefits

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 of the Appendix, Figure 3-22 displays the new locations for the 20 optimum evacuation bus stops.

Figure 3-22

Optimum 20 Bus Stop Locations 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 number of bus stops clustered in the region located northwest 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 northeast 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 3-23. This scenario contains all the same bus stop

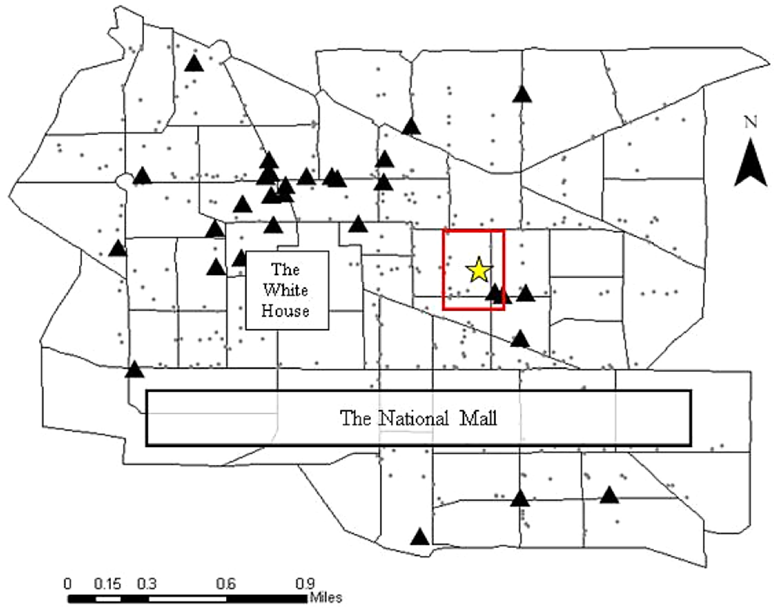


Figure 3-23

Optimum 30 Bus Stop Locations after Grid Implementation

locations as the 20-bus-stop scenario but has an additional 10 locations. The new grid equations added to the formulation allow for the 10 new locations to be more evenly distributed throughout the case study area. There is still a large number of stops located to the northwest 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 expanded, but certain regions (i.e., the eastern portion of the case study area) are still lacking evacuation bus stops.

Figure 3-24 depicts the major improvement of the addition of the new constraints to the optimization model. In the first trial of the optimization model—the

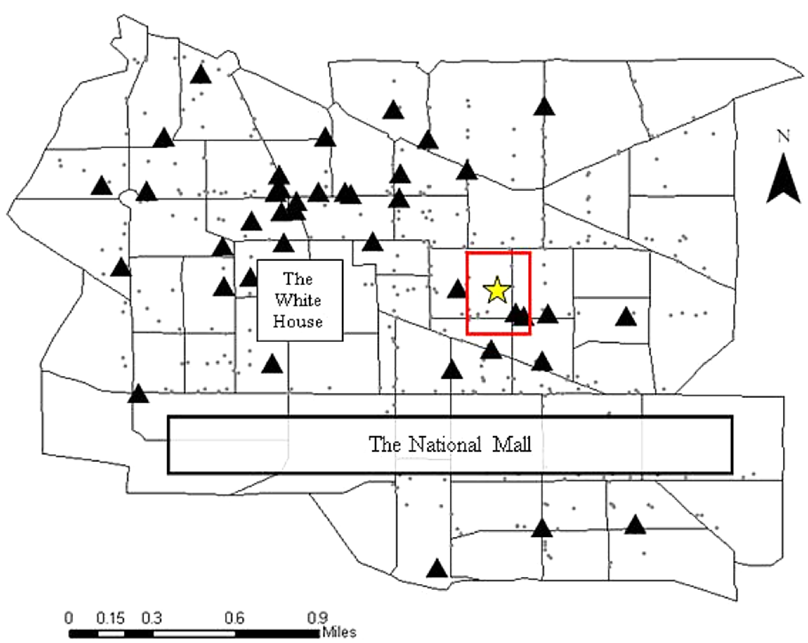


Figure 3-24

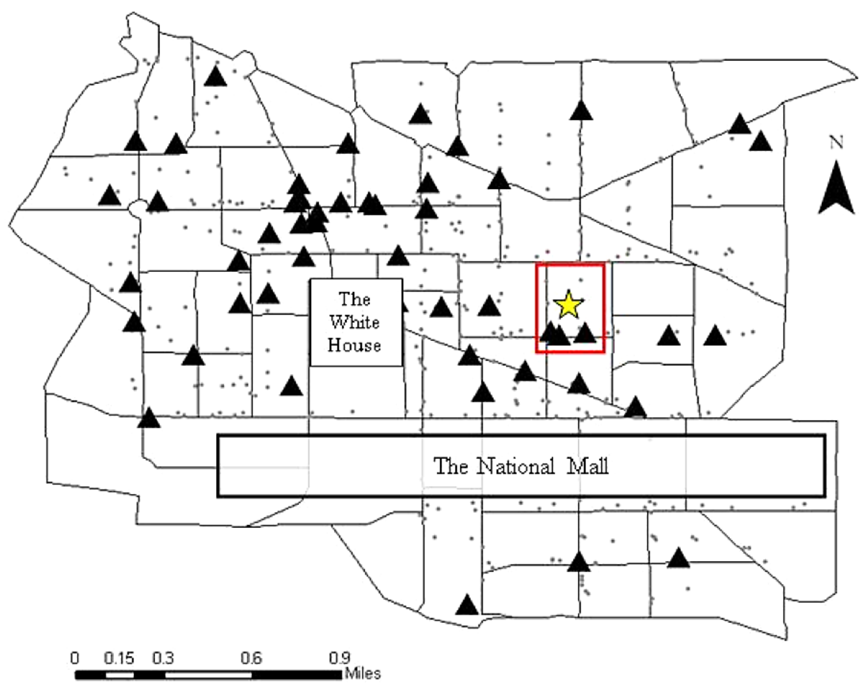
Optimum 40 Bus Stop Locations after Grid Implementation

40-bus-stop scenario—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 four evacuation bus stops. These bus stops are crucial for evacuation purposes because of the large number 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 3-25). Noteworthy new locations include three bus stop locations in the northeastern portion of the case study area. In the previous maximum bus stop scenarios, this area did not contain anyevacuation bus stops. The 50 locations represent the case study well spatially and provide evacuation service to special needs populations in all the regions. The benefit function did not include tourists as one of the special needs 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 3-25

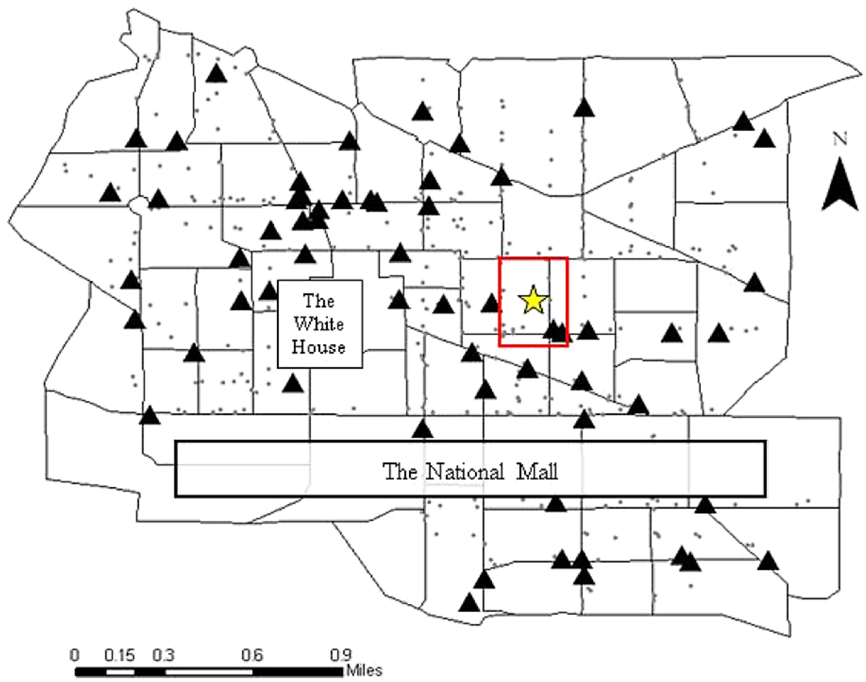
Optimum 50 Bus Stop Locations after Grid Implementation



The locations selected 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 scenario 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 3-20 to Figure 3-26. If the optimization model has the

Figure 3-26

Optimum 60 Bus Stop Locations after Grid Implementation



ability to select more optimum locations, more TAZs will contain an evacuation stop, giving a more widespread service area of bus stops.

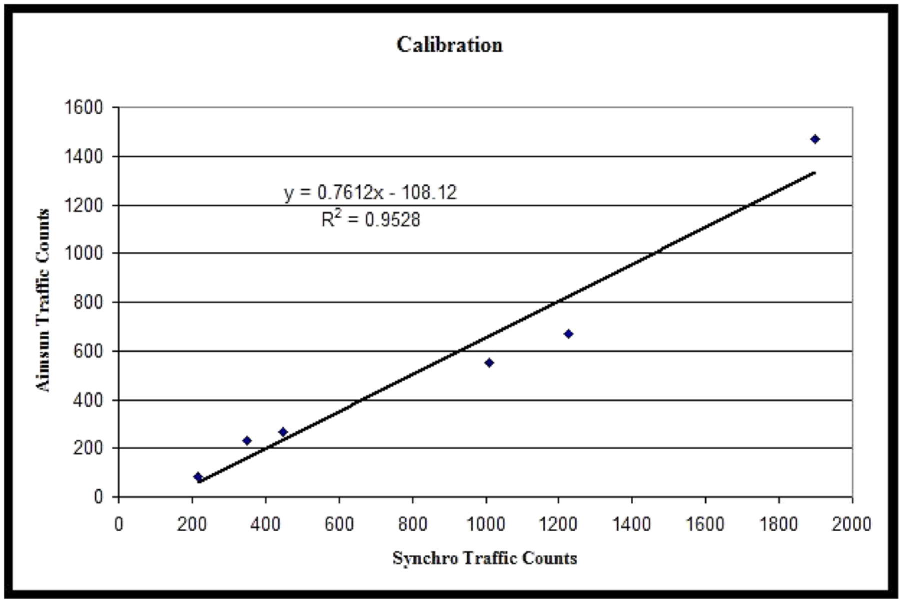
Network Calibration

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 hours and were provided for a one-hour interval, but the exact time of the counts was unknown. The time used for calibration was 10:00 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 evaluated 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 proportion 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 3-27). Default parameters such as car following, stopping, and lane-changing behaviors had to be modified to reach this result.

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

Figure 3-27

Final Calibration Results



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 St., 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 were obtained, the actual time of the counts was unknown. This affects the calibration of the model because the model is being calibrated using O-D matrices for a particular time of day. The pattern of traffic demand behavior normally follows the graph shown in in Figure 3-28. By not attaining exact field traffic counts, an accurate calibration is difficult to conduct.

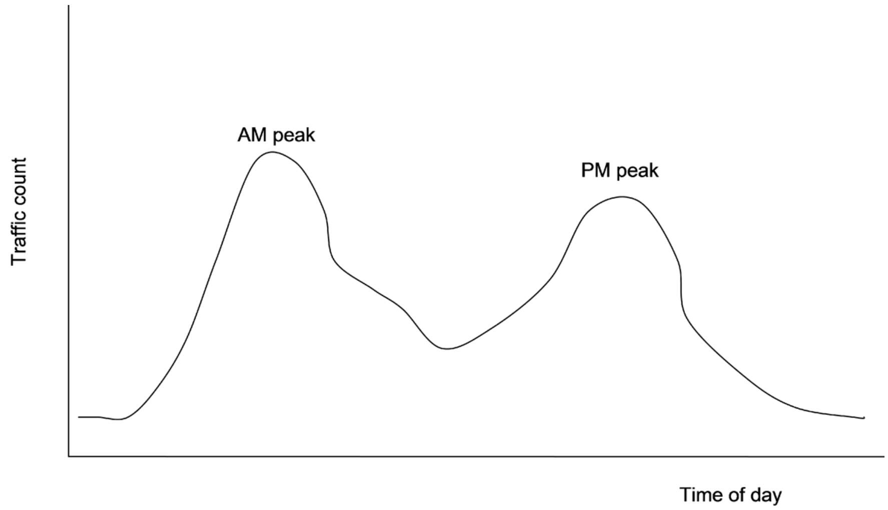
Simulation Results

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 section.

The definition for each measure of effectiveness (MOE) is defined as follows by 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 route. This is the mean

Figure 3-28

Traffic Demand Peak Periods



time of travel for each public transit vehicle from time of entrance until exiting the network. (This MOE was chosen despite some public transit routes consisting of more travel distance than other public routes.) Last, 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 gridlocked intersections.

A standard dwell time was calculated and applied to all evacuation bus stops. Using standards set by the *Highway Capacity Manual*, 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 equipped with either a low-floor ramp or hydraulic lift. The wheelchair 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 types of wheelchair loadings, a standard deviation of 60 seconds was applied to the dwell time.

Results were recorded for five different replications for the five different maximum number of evacuation bus stop location scenarios. One replication would take on average four hours to simulate using the batch function of Aimsun. If the replication was simulated using the animation function, the simulation time was extended to six 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 3-29. 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 of the congestion of all the buses serving the same small number of stops. The buses in this scenario had to be set to a very close headway (approximately 2 minutes) to reach the required number of bus trips to evacuate the case study area. Due to the minimum headway interval and large dwell time, buses serving the same stop formed larger queues than the other scenarios. The lowest delay time was experienced by the 60-bus-stop scenario.

Figure 3-29

Average Delay Time

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 serving its assigned stop. Travel time is also dependent on which roadways the bus route serves and the level of service. In this research, it was decided to find the average travel time of all the evacuation bus routes serving the entire case study area.

The results found for travel time are consistent with the results obtained for delay time (Figure 3-30). 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, which 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 scenarios). The lowest average travel time resulted from the 60-bus-stop scenario. The ranges for average travel time for all five scenarios were all within 50 sec/mi. This might seem as a minor difference, but when dealing with evacuation, time is of the essence.

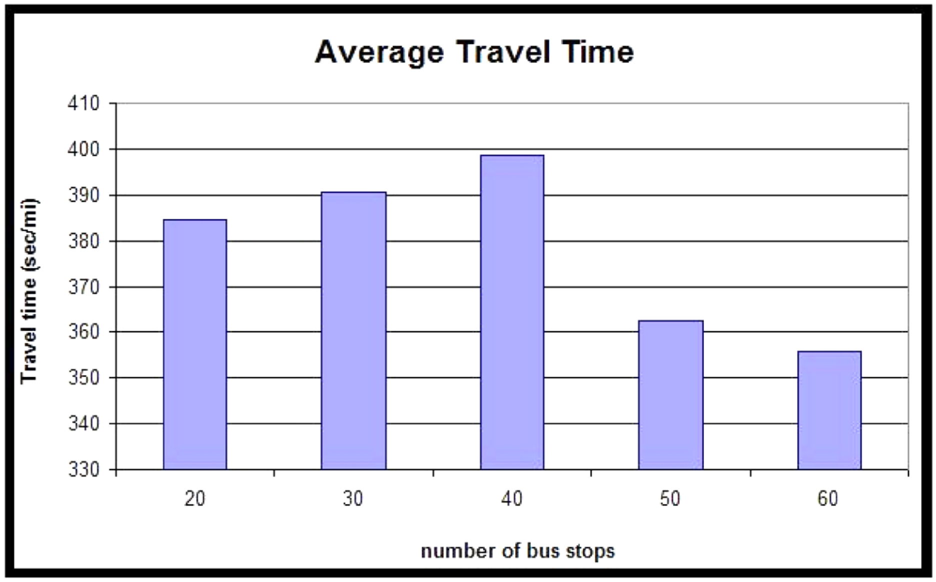


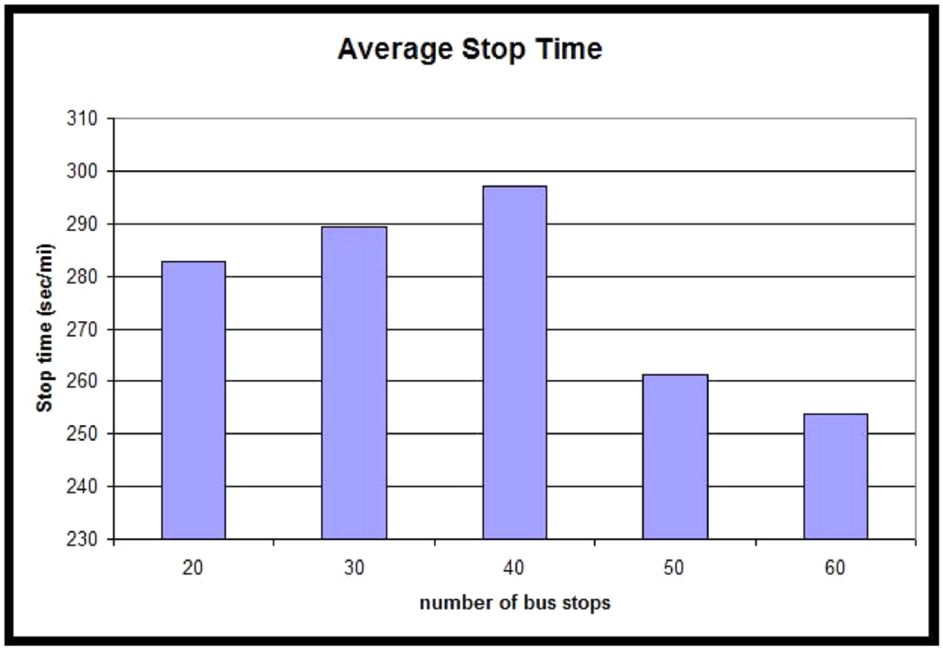
Figure 3-30
Average Travel Time

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 3-31. 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.

Beginning the simulation scenarios with 20 evacuation bus stops and increasing the number of stops by 10 for each succeeding simulation, the worst scenario was found. The 40-bus-stop scenario yielded the highest delay, travel, and stop times and should not be implemented for evacuation. This could be due to the bus stop locations still requiring a large number 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 decreases from 50 to 40, reducing the delay, travel, and stop times. Also, the bus routes required for this scenario might require longer evacuation travel distances.

After reviewing all the results for each MOE, it can be seen that the 60-bus-stop scenario produced the most efficient evacuation time. The delay, travel, and stop times were all the lowest when compared to the other simulated scenarios. This is due to the lower number of 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 stops are located along the border of the case study area, allowing for shorter bus evacuation routes.

Figure 3-31
Stop Time



SECTION 4

Case Study 3: Transit Signal Priority for Emergency Evacuation—Mitigating Disaster

Background Information

Challenges in Evacuation

Emergency evacuation procedures vary drastically, depending on the perceived threat level. This is due to the type and scope of the potential threat. The evacuation methodology put into action is heavily dependent upon the demographics of the area and the type of emergency. The optimum evacuation in response to a chemical spill will be different from that for a nuclear incident. Evacuations are classified by two different factors: time and space. The time aspect is, with regard to notification, the duration until the loss of life or property can be expected. Time has two categories: short-notice and no-notice. Evacuation resulting from events with 24–72 hours of advanced notice, such as hurricanes and wildfires, are considered short-notice evacuations. Events corresponding to notification less than 24 hours are no-notice evacuations (Chiu 2007). The space component refers to the size of the area that may be affected by the impending threat. Therefore, there exist four emergency evacuation types: small scale—short and no-notice, and large scale—short and no-notice. Each one has its own aspect for consideration, but large-scale emergences require the most research consideration due to the large area affected and the intricacies of coordinating a response.

A large-scale evacuation can affect hundreds, if not thousands, of people, homes, and businesses. In an evacuation with ample warning, resources are in place and time-release schedules, which are developed to optimize the capacity of the road network using staged evacuation, can be employed (Chen et al. 2008). Development of plans in the event of a no-notice evacuation is crucial. Each minute matters, and time cannot be wasted in deciding the best course of action. No-notice evacuations require inhabitants of the area to vacate the region from their current location immediately without returning home first. These events have an instant and devastating impact on traffic networks. Such a large increase of traffic demand inevitably leads to congestion, delays, and possible loss of life.

Transit in Emergency Evacuation

Urban areas with high population densities and massive commuter influx form numerous obstacles for regional planners to overcome when considering emergency evacuation plans and procedures. However, urban areas do have some advantages with regard to emergency evacuation. Oftentimes, highly populated cities are more accustomed to sudden and drastic changes in traffic demand and have traffic infrastructure in place to assist in high-demand situations: traffic control plans, ITS, partial lane reversal, etc. Additionally, many urban areas have transit systems: streetcars, subways, and other light rail systems, both single and double. Previously, buses have shown significant results in assisting in the evacuation of large populations (Wendell 2006; Mastrogiannidou et al. 2009).

The advantages of public transit systems in evacuation are vast. One bus can hold as many as 55 people, who would have otherwise used personal vehicles, adding to the congestion on roadways. The use of buses and other transit system can greatly reduce the congestion and overall clearance time during evacuation (Mastrogiannidou et al. 2009). Transit operators have constant network-wide communication that can be used in various unforeseen situations that arise during an emergency. Additionally, transit is available for people who could not otherwise evacuate, namely car-less populations. Furthermore, transit operators are more accustomed to dealing with event-related traffic congestion, lane closures, and rerouting based on external stimuli (Scanlon 2003).

Nevertheless, improper planning with regard to transit operations in these situations limits the possible resources available to assist the evacuation effort (Renne et al. 2008). Transit operators need to be informed of their duties in the event of an emergency. City officials must know beforehand whose responsibility it is to allocate transit operators to units (buses, streetcars, subways, etc.) and which units to allocate to a region, route, or area. Prior to Hurricane Katrina, New Orleans had in place a plan to use school buses in the event of an evacuation, but, due to improper planning, these buses were never used because the plan did not dictate who was responsible for this procedure (Nigg et al. 2006).

Problem Statement

The goal of this research is answer a single question: During an urban evacuation, is it advisable for regional planners to allow transit units signal priority in cases where police-assisted traffic controls are not an option? Standard practice for emergency evacuation is to place police officers at intersections throughout the evacuation area. However, this is not always an option. When circumstances place officers in immediate danger of loss of life or limb, the officers are removed from the situation. In cases of major disaster where environmental factors such as the presence of fire, chemical plume, or radioactive fallout (nuclear-contaminated wind and dust) do not permit police presence at intersections, regions are forced to rely solely on in-place traffic control measures. During the attack of 9/11, literally hundreds of first responders lost their lives when the World Trade Center came crashing down (9/11 Commission Report 2004). Unlike the World Trade Center, where the threat of disaster was unknown, intentionally exposing first responders to extremely hazardous conditions, where loss of life is not a possibility but the ultimate logical conclusion, is not something that is practiced.

Evacuation research can lead to saving lives in the time of emergency. High-density urban areas form a unique problem for emergency planning. Transit can assist in the egress of special needs populations, carless populations, and otherwise stranded people. Transit units, as in the form of buses, are in great demand. With only a finite number of available units, buses will be required to make multiple trips in and out of evacuation zones. Therefore, it is within reason that some regional municipalities would allow transit priority to hasten trips made by buses. Minimizing bus travel time allows for more trips to be made, optimizing the number of bus units available. However, studies in the past have shown that during times of high roadway demand, transit priority causes major delays for vehicular traffic (Dion et al. 2004; Smith et al. 2005). Therefore, there exists a tradeoff to be examined between allowing transit priority during times of emergency evacuation to increase the number trips made by buses to special needs areas and the cost of this priority to the overall egress of the evacuation traffic.

Methodology

The methodology of this research is divided into two components: evacuation demand modeling and transit signal priority (TSP) operations. General traffic modeling and background demand modeling are discussed in the later section on Traffic Network Modeling, as these characteristics are case-specific, unlike the trip generation and distribution models for evacuation, which are general and can be applied to other existing traffic networks. Evacuation demand modeling focuses on development of the mechanism of the four-step traffic modeling procedure for the evacuation. This section deals with how this is applied to the micro-simulation environment. The transit operations and signal priority sections outline the process by which the transit units operate within the simulation surroundings, with and without priority. Figure 4-1 illustrates how these two components are developed and integrated into a simulated network.

Starting with the data set on the left of Figure 4-1, street geometry, signal timing data, traffic counts, and transit information such as schedule and stop locations were fed into the TSP logic and the simulation platform directly. The TSP logic allows transit units the right-of-way when approaching intersections. This process is highlighted in detail in the previous section on Transit Operations and Signal Priority. With the bases of the traffic model and transit priority developed, the focus was to turn the traffic model into an evacuation model by adding the evacuation demand. Looking at the data set on the right, socio-economic data, census data, and regional evacuation data were passed into the emergency evacuation trip generation and trip distribution models. These models are discussed further in following section. From these models, an evacuation O-D matrix was generated. This matrix was then used in the simulation platform to create a realistic

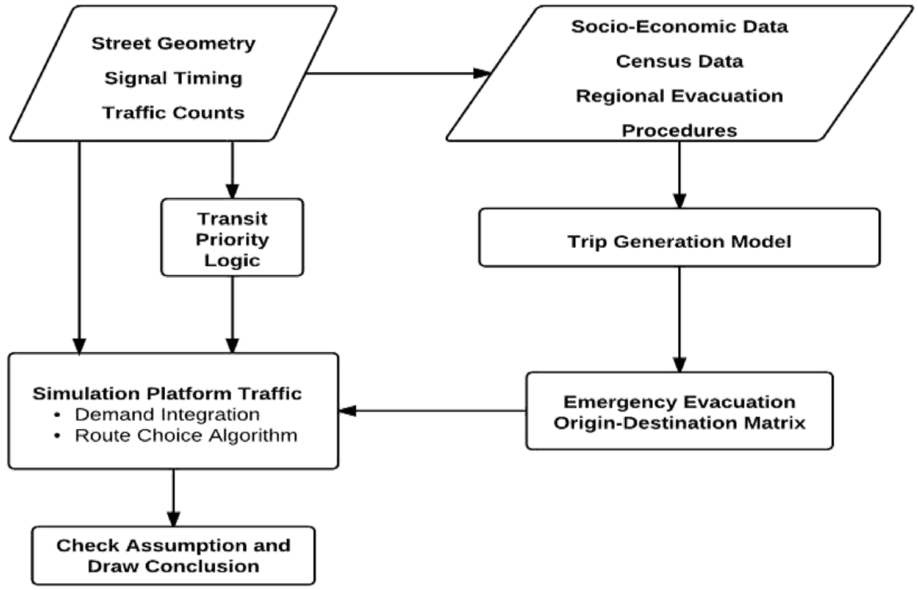


Figure 4-1

Flowchart of Methodology

emergency evacuation traffic model. From this simulation model, MOEs such as travel time, evacuation clearance time, delay time, etc. were calculated. These MOEs were then extracted from the simulation platform for statistical analysis. From there, assumptions were checked, conclusion are made, and recommendations are brought forward.

Evacuation Demand Modeling

For this research, an evacuation trip generation and trip distribution model for a downtown urban area was developed. From these two models, the evacuation O-D matrix was created. Mode choices were reduced to personal vehicles and transit. All other modes were assumed to have a marginal impact on the traffic network and represent an insignificant reduction in travel demand. Route choice was modeled using a variation of the Dijkstra label setting shortest path algorithm developed in the micro-simulation platform.

Trip Generation

For this research, an urban downtown district, weekday peak, evacuation traffic demand model was developed, advancing on work done by Noh et al. 2009. Because the trip generation model for evacuation demand and background demand were developed separately, the trip generation model for evacuating traffic is in units of vehicles, allowing the user the ability to combine the result of both demand models into a single simulation network. Because these models were developed separately, this approach is ideal. By converting trips into vehicles at the generation stage, the output may be directly incorporated into the results for the background traffic demand model. Within the evacuation demand model itself, modelers have the ability to increase the rideshare proportion associated with a no-notice evacuation. For this model, *i* is the set of all evacuation TAZs, *j* is the set of all other TAZs, and *t* is the set of time periods beginning at the peak hour and lasting until traffic from i is rerouted away from the disaster area. Equation 25 can be found in the Appendix.

This model assumes that all employees of the downtown district work a typical 9:00 am to 5:00 pm workday and that people will not be able to make a return trip home during the emergency. People without vehicles (special needs populations, school children, transit commuters, etc.) will evacuate by some other means (transit, Metro, bus) and will not make a significant contribution to the personal vehicle traffic in the form of additional vehicles. In addition, due to the high demand of other means of evacuation (transit, Metro, bus, etc.), all people able to evacuate with personal vehicles do so. This model is valid only for an urban downtown business district.

Trip Distribution

The general form of the trip distribution model was adopted from Southworth (1991) and modified for this research. This methodology uses two equations to govern evacuee trip distribution: the safe-zone probability model and the safe-zone selection model. Safe zones are areas a predefined distance away from the disaster site. These locations are chosen based on numerous criteria, which are dependent upon the demographics of the region and the specifics of the event. The safe-zone probability model, Equation 26 in the Appendix, is the probability an evacuee will select zone *j* as a safe zone.

The perceived desirability of zone *j* as a safe zone are case-specific functions that can be depend upon evacuation corridors, police routing, selected facilities, etc. Travel distance between zone *i* to zone *j* is the Dijkstra short path tree. This tree is discussed further in the following section on Evacuation Route Choice. The safe-zone selection model is the number of vehicles traveling from zone *i* to *j* as a result of the evacuation. Equation 27 can be found in the Appendix.

Evacuation Route Choice

Route choice from origin to destination is calculated using a variation of the Dijkstra label setting shortest path algorithm developed by Aimsun. The Dijkstra label setting shortest path algorithm finds the shortest path from a given starting point (or node) on a graph to all other nodes (Dijkstra1959). For routing problems, the Dijkstra algorithm is stopped once the destination node is reached. The resulting tree is the shortest path from origin to destination (Aimsun MicroMeso User's Manual). Using the center (by area) of each evacuation TAZ as the origin node, the shortest travel distance to each safe zone is calculated. For the purpose of the application, road segments are used as links, with penalties associated with turn movements. This form of route choice model is ideal for studies using evacuation corridors. For more information about turn penalties or link cost function, consult Aimsun MicroMeso User's Manual v6, Section 10.4.1.3, Shortest-Path Algorithm.

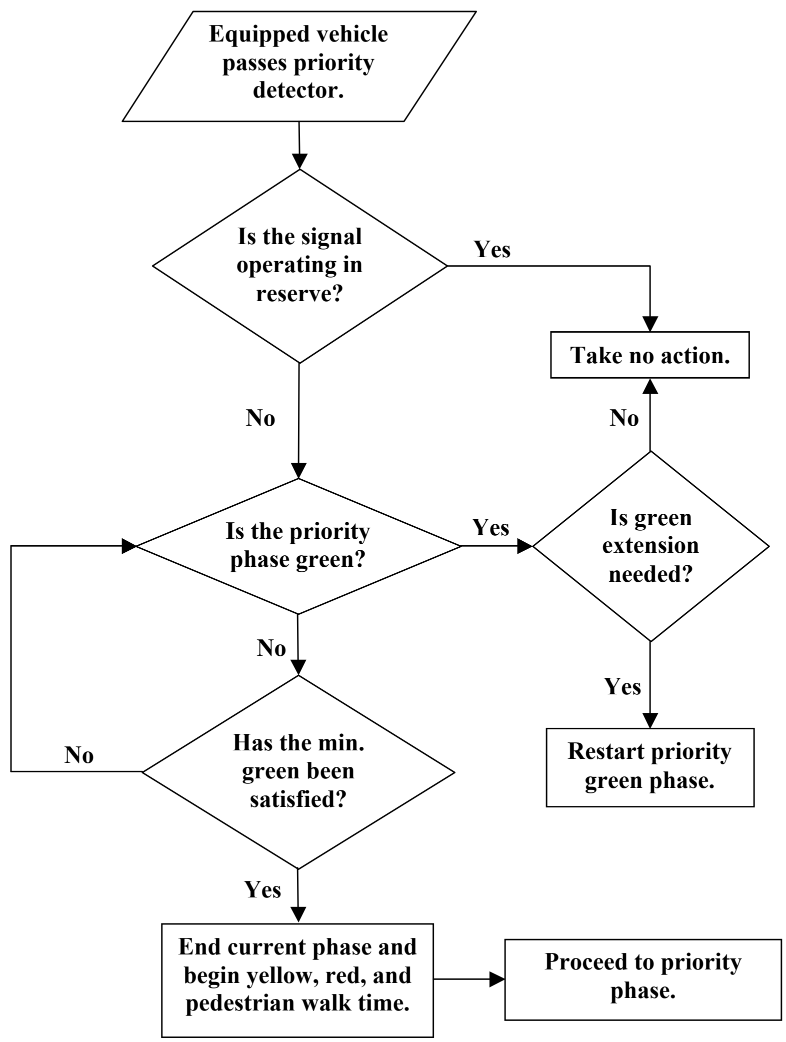
Transit Operations and Signal Priority

Transit operations within the simulation environment are designed to mimic reality. Transit units such as buses adhere to the schedules, make stops, and interact with traffic. For this research, the transit operations are identical to the case study and discussed in further detail in the section on Bus Operations. TSP, however, is developed independently of transit operations due to the fact that the case study does not currently allow transit priority at intersections.

TSP logic is designed with two goals in mind. The first goal is that the logic must decrease transit travel time between 9 and 35 percent to match the results seen by practitioners in the field; this decrease in travel time must have only a marginal effect on personal vehicles, i.e., a less than 5 percent increase in travel time. The second goal is to have a seamless interaction with the traffic simulation environment. The logic must be diverse so that it may be programmed into the simulation. Figure 4-2 visually displays the logic in flowchart format.

Figure 4-2

Signal Priority Logic



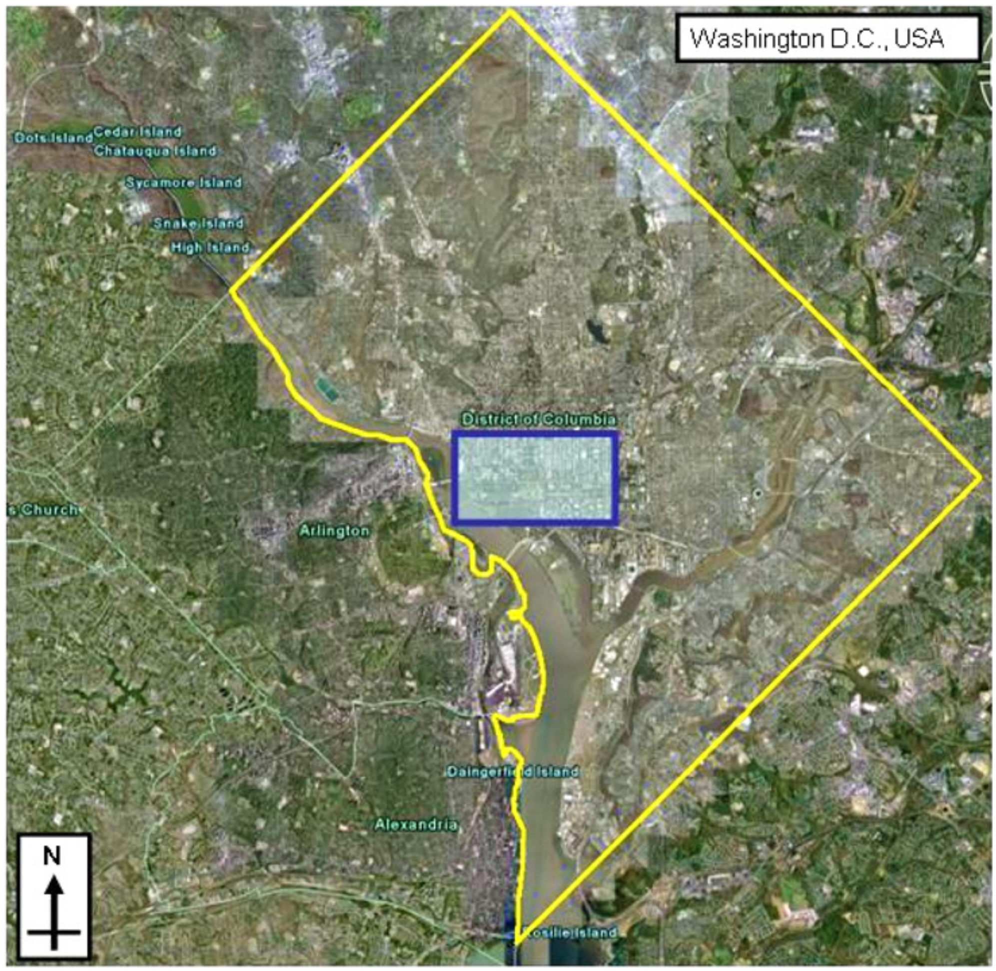
An equipped vehicle is one that is capable of communicating with priority-enabled traffic control devices. As this vehicle passes a priority detector, the priority request generator is activated; simply put, the vehicle "checks in" to the intersection. Predefined into the traffic controller, the priority request server knows the location (distance upstream from the intersection) and the route of the vehicle. The first question the priority request server must answer is, Is the signal operating in reserve? Reserve is defined as the time that priority is not available. From the practices observed in the literature review, this duration is set to one cycle length. If the signal is operating in reserve, no action is to be taken. When the signal is not in reserve, the next questions to be asked by the priority request servers are, Is the priority phase green? Is the phase that is being requested the same as the phase currently being served? In this case, the server must know if a green extension is needed. Is the vehicle predicted (based on detector distance and travel speed) to pass the stop-line (check out) before the onset of the yellow time? In cases where the vehicle is predicted to "check out" in time, no action is taken. When the priority request server predicts the end of the cycle, it restarts the priority green phase. If the vehicle approaching arrives when the priority phase is not green, the priority request server must know whether the current phase has completed its required minimum green time. The minimum green time is the pre-defined green time a phase is required to receive, regardless of the priority request. Once again, from the literature review, this logic uses a duration of 10 percent of the cycle length. If this is the case and the minimum green has not been satisfied, the request is delayed until such time. Once the minimum green has been satisfied, or in the case of a priority request generated after the minimum green, the priority request server proceeds with the request. This is done by ending the current phase, advancing to the yellow, all-red, and walk time, then immediately proceeding to the requested phase.

Case Study Application

A case study of Washington, D.C. was used to test the formulations presented in the methodology section. Washington, D.C. is the capital of the U.S. and home to many vital governmental buildings and monuments, making it an attractive location for a terrorist attack and thus a probable location for emergency evacuation. Washington, D.C. has a population of 591,833 citizens and a daily commuter influx of 410,000, making it an ideal candidate for a transit priority system (Longley 2005). In addition, this region brings with it a diverse population that depends upon a dynamic road network to deliver them in and out of the city. Because of the city's numerous attractions (White House, Smithsonian Museums, Capitol Building, etc.), tourists from all over the world visit the region (Cooper 2009).

Figure 4-3 depicts the boundaries of Washington, D.C. outlined in yellow. Defined on three sides by a diamond configuration and the Potomac River on the fourth, this area is 68.3 square miles. Outlined in blue and located in the center of the figure is Central DC, the downtown business district of the metropolis (WMATA 2009). Central DC is the region that resides south of NW Q St., north of the Southeast Freeway, west of NE Capital St., and east of the Potomac River. Within these boundaries are the vast majority of the region's businesses, weekday population, and tourist attractions.

Figure 4-3
Washington, D.C.



Source: Google Earth

Case Study Area

The study area is a 14-intersection corridor located in the southeast corner of Central DC: NW 7th St. from SW E St. (South) to NW Pennsylvania Ave., west to NW 12 St. This area is located just a few blocks west of the U.S. Capitol building. Figure 4-4 illustrates the study area and the Capitol by outlining the study corridors in blue with the bordering streets in black. This area was selected because of its location with regard to the major Metro stations within the city. Moreover, this corridor plays a crucial role in the city's evacuation plans, as discussed in the section on Washington, D.C. Evacuation Plans.

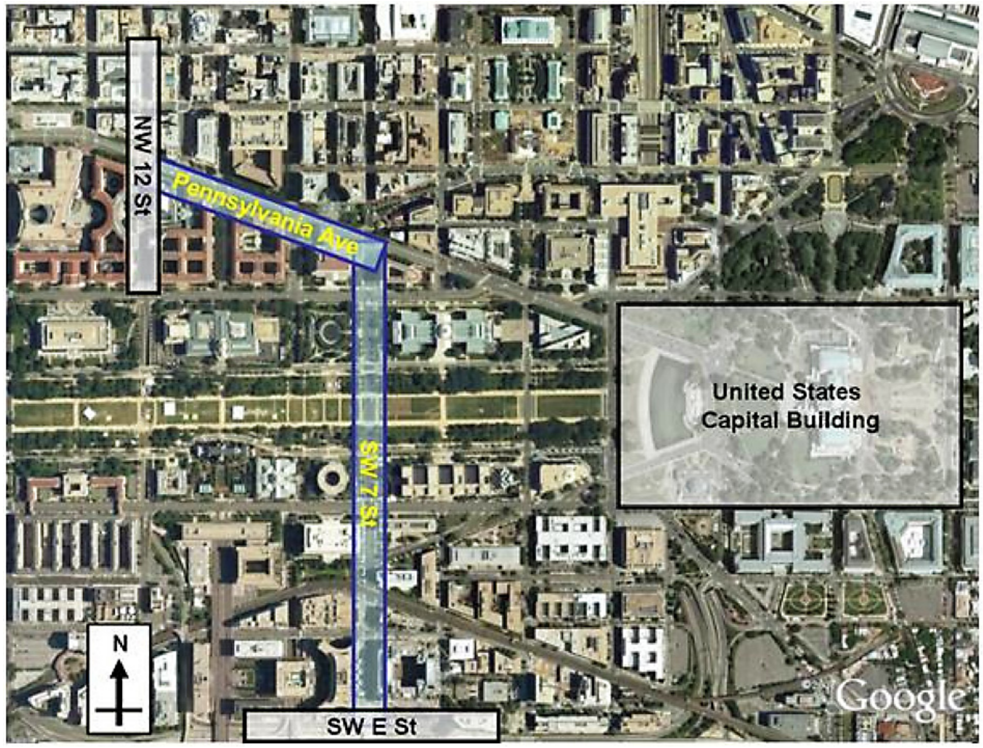


Figure 4-4
Study Corridor

Source: Google Earth

Washington, D.C. Public Transportation Network

WMATA is the operating and governing body controlling public transportation in Washington, D.C. It is one of the most reliable and efficient public transportation networks in the country. Founded in 1967, WMATA was a joint venture among Maryland, Virginia, and Washington, D.C. It combined both public and private transit organizations within the region to increase the network efficiency. In 1973, WMATA took over four regional bus operations under the name Metrobus. It currently serves 319 routes on 174 lines, bringing service to 12,227 bus stops. Of those 12,227 bus stops, 597 are owned and operated by WMATA. Metrobus operates approximately 1,500 buses and offers services 24 hours a day, 7 days a week.

Metrorail started in 1976 and now serves 106 miles of rail, with 86 stations throughout the area. (Figure 3-2 shows the area serviced by Metrorail.) Metrorail uses five lines (Blue, Green, Yellow, Orange, and Red) that traverse both above and below ground. Within the borders of the case study exist two Metrorail stations, L'Enfant Plaza on SW 7 St. & SW D St. and Archives–Navy Memorial–Penn Quarter on NW 7 St. & NW Pennsylvania Ave. Just north of the study corridor are two additional stations, Metro Center and Gallery Place/Chinatown on NW 7 St. & NW G St. and NW 12 St. & NW G St., respectively. L'Enfant Plaza, Metro Center, and Gallery Place/Chinatown constitute the three most traversed Metro stations within Washington, D.C. (WMATA 2009). L'Enfant Plaza is the crossover point for four of these lines (Blue, Green, Yellow and Orange), making it the largest hub for Metrorail operations.

Combined, Metrorail and Metrobus serve nearly 3.4 million passengers yearly on roughly 1,500 miles of track and street. Metrorail and Metrobus constitute the second and sixth largest rail and bus systems in the country, respectively. During fiscal year 2009, these two modes of public transportation combined to serve 356.7 million trips (WMATA 2009). Metrorail offers service to the suburbs in Maryland such as to Montgomery and Prince George, as well as suburbs in Virginia, such asAlexandria, Arlington, and Fairfax. For the most part, Metrorail and Metrobus are used by commuters as a low-cost alternative to personal vehicles. Additionally, much of the tourist populations visiting the capital takes advantage of this mode of transportation.

Both Metrorail and Metrobus units meet the standards set by the Americans with Disabilities Act (ADA) for providing access for persons with disabilities. The Metrorail fleet consists of five types of rail car: Alstom 6000 series, Breda 2000/3000 series, Breda 4000 series, CAF 5000 series, and the Rohr 1000 series. These cars each have the same 75 ft x 10 ft dimensions and allow adjustable/foldable seats to accommodate wheelchairs. WMATA recently implemented gap reducers to minimize the space between the railcar and platform to provide a more accessible entrance and exit for persons with disabilities. All units within the Metrobus fleet have floor-lowering ramps with the required hydraulic lifts to oblige wheelchair users. Users of Metrobus who have disabilities are offered priority seating directly behind the bus driver.

Washington, D.C. Evacuation Plans

To improve upon the current evacuation procedures for the region, first, the existing plans must be reviewed. The current evacuation plan for Washington, D.C. is defined in the District Response Plan: Emergency Transportation Annex (ETA). Developed in 2006, the ETA presents the plans, organizational structure, and procedures used in the event of a disaster resulting in the need for a regional evacuation. This plans call for the use of 19 major corridors to assist in the evacuation process. These corridors are the primary evacuation routes and are all major arterials that span from Central DC to the I-495 beltway. Secondary corridors, defined by DDOT, are selected routes that connect major corridors with one another. These routes are to be used in the event that one of the major corridors is closed or otherwise damaged during the emergency and traffic needs to be routed to a different major corridor. (Figure 3-3 displays the 19 major corridors described in ETA. Note that within the study area, Georgia Ave. (NW 7 St.) and NW Pennsylvania Ave. are two of the major corridors for evacuation.)

The ETA states that "the district will enact a phased release in response to emergencies that to do not pose an immediate threat to life or health in a select location." A phased release is a staged evacuation plan in which the evacuation is staggered to allow selected areas full access to the road network. In addition to this strategy, the ETA states that all intersections will operate on PM peak-hour signal-timing plans unless otherwise specified.

All transit operations during an emergency are to be put under the control of WMATA. Metrorail and Metrobus, as well as all other transit operators within the region, are directed to maintain normal operating procedures, schedules, and routes so long as they are not directed otherwise. In the event an emergency requires additional resources (buses), an incident commander will notify WMATA for assistance. In the case that operations of Metrorail need to be stopped, additional surface transportation will fill the transportation mode gap until such time as Metrorail can resume operations.

Traffic Network Modeling

The Washington, D.C. road traffic network was developed using the microscopic traffic simulation software platform Aimsun Professional 6.0.5. This model encompasses the study area on SW 7 St. from SW E St. to NW Pennsylvania Ave. and west on NW Pennsylvania Ave. to NW 12 St. Within the model exist 14 intersections and 83 street segments totaling 5 miles in length, with 14 miles in lane length. The streets intersecting the primary corridor (all streets that are not SW 7 St. or NW Pennsylvania Ave.) terminate at the stop line of the upstream intersection. These streets, in order from south to north (as they intersect the main corridor), are:

- SW D St.
- SW Virginia Ave.
- SW Maryland Ave.
- SW Independence Ave.
- SW Jefferson Dr.
- SW National Mall Crossing
- NW National Mall Crossing
- NW Madison Dr.
- NW Constitution Ave.
- NW Pennsylvania Ave.
- NW 9 St.
- NW 10 St.
- NW 11 St.
- NW 12 St.

These street segments were modeled in Aimsun 6.0.5 to match detailed GIS shape files and longitude and latitude match satellite photographs received from DDOT. The geometric features observed from these files were compared with field observations to check their validity. Upon comparison, these features (number of lanes, turn pockets, crosswalks, etc.) match the satellite images accurately. A representation of this model can be seen in Figure 4-5.

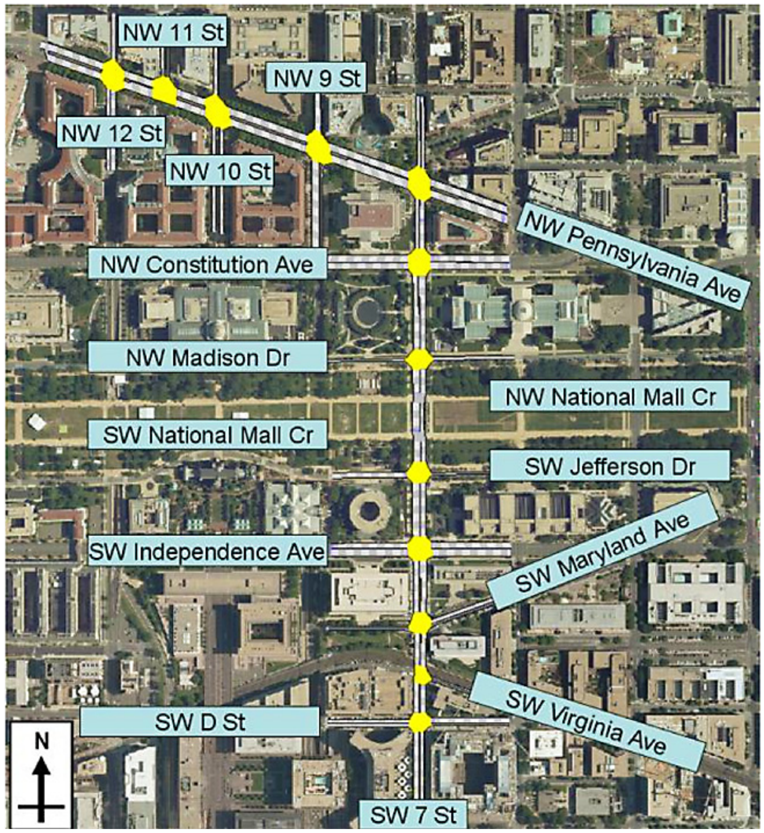


Figure 4-5

Microscopic Simulation Environment

Signal Timing and Background Demand

Signal timing data for this research was provided by DDOT. To acquire these data, a personal request was made by the Transportation Research Laboratory at Florida Atlantic University. DDOT obliged and sent signal-timing plans divided into schedules, AM peak, PM peak, and midday off-peak hours. This information was delivered in the form of Synchro 7 optimization software files. Synchro has the ability to provide advanced coordination between traffic-control devices at separate intersections. This form of information dissemination is common in the traffic-engineering field. The traffic-control information from these files was copied directly into the simulation environment.

In addition to the signal timing data, the Synchro 7 files provide traffic count and street flow information collected and developed by DDOT. This count information, collected in 2006, is used by DDOT for its four-step modeling process. From this process, DDOT develops traffic flow information for individual links. Therefore, using this count and flow information to develop traffic flow for background demand for this research is an accurate assumption. By using this information, trip generation, trip distribution, mode choice, and route choice models did not need to be developed specifically for this study. The results of these models, previously developed by DDOT, were used instead.

Modeling Metrobus Operations

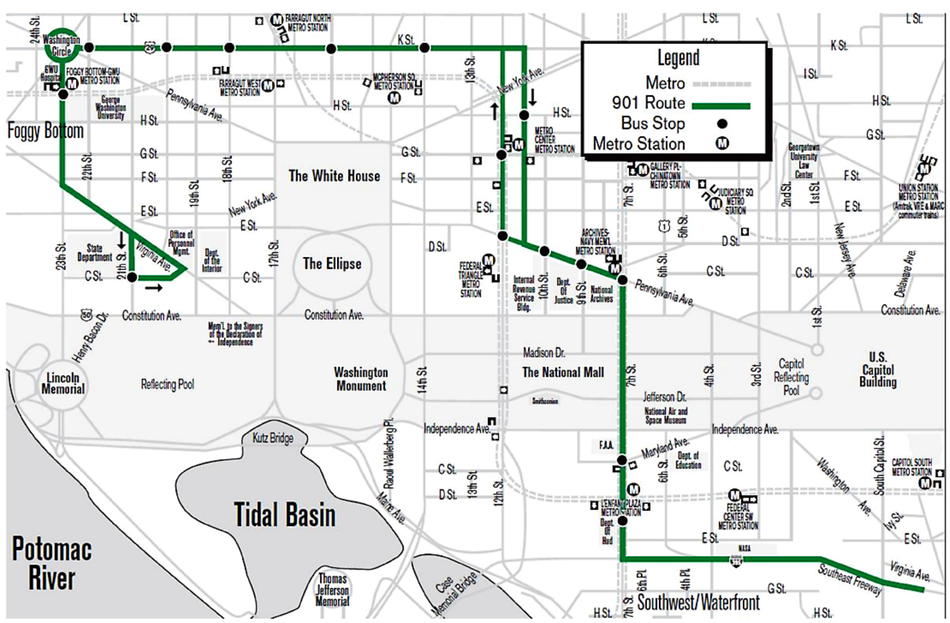
Within the borders of the case study exist 34 Metrobus lines. For the purpose of this research, some bus lines were excluded from being modeled in the network. These 34 lines were subject to two criteria: each line must involve a thru or left-turn movement, and each line must travel through more than one intersection within the study corridor. That is to say, buses that do not require priority (right-hand turns only) or buses who simply pass through the corridor and do not traverse it are excluded. Based on this, 17 lines were removed from consideration, leaving 17 lines to be modeled.

Each of the 17 bus routes were coded into the simulation network. Bus stop locations were mapped using GIS shape files downloaded free from the Washington, D.C. GIS online database. Mean bus stop duration and standard deviation were manually coded. These values are 12.29 seconds and 13.47 seconds, respectively, as researched by Dueker et al. 2004. Bus departures—the time at which the bus arrived into the network—were found using a trial and error method. Bus stop arrival times are known from published schedules; travel times to these stops were estimated in the simulation environment. By testing and modifying bus departure times, arrivals were coded on schedule. Within the network, bus departure times for each bus operation (roughly 300 individual bus departures) were manually coded starting at 4:00 pm until 10:00 pm to be sure that all operations throughout the entire study period were captured.

From the 17 lines within the network, two were selected to be evacuation bus routes, 901 and 905. These routes were selected for their location and serviceability. These two lines navigate the entire length of the corridor, entering northbound from SW 7 St. and exiting westbound NW Pennsylvania Ave., and vice versa for southbound trips. Figure 4-6 and Figure 4-7 show the route trajectories within Central DC.

Figure 4-6

Bus Route 901



Source: WMATA, 2010

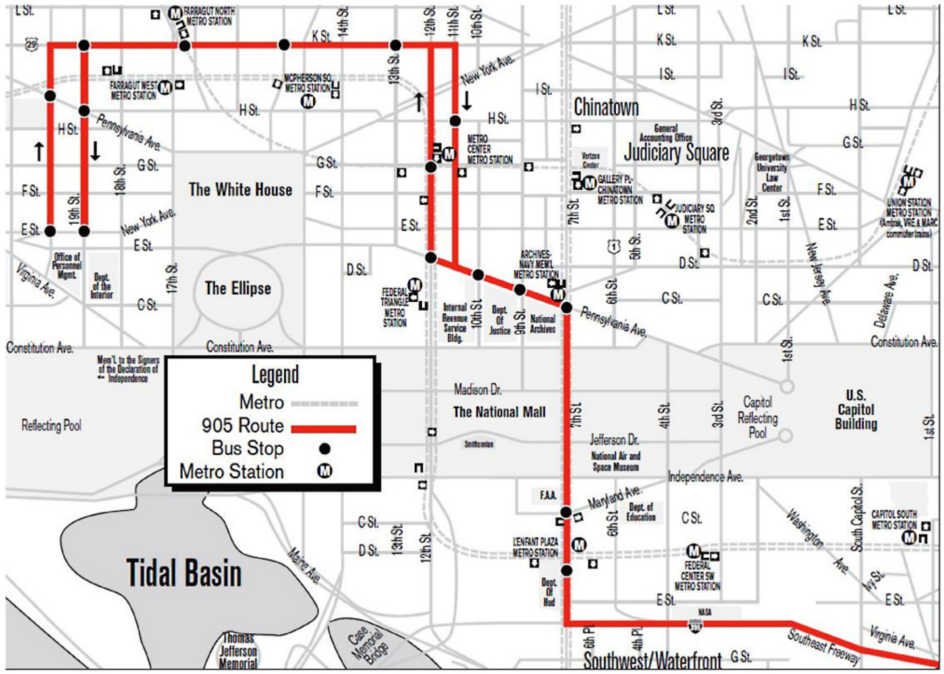


Figure 4-7

Bus Route 905

Source: WMATA, 2010

Network Calibration

After development of the microscopic simulation environment was the painstaking task of calibration. Calibration is the process by which the model is transformed for one of theory to one that represents reality. For this, every aspect must be examined in close detail, from traffic counts to the underlying algorithms that govern driver behavior. These attributes are modified in tandem with one another to form the conditions observed in the field. This task mandates tedious attention to detail and many hours, if preformed correctly.

Field Samples

To capture the field conditions using a "floating car," travel time runs were conducted during the PM peak hours on January 12, 2010, within the study corridor. The floating car technique requires a probe vehicle to measure travel time on road segments. The probe vehicle attempts to pass as many vehicles as pass it in an attempt to achieve a net gain of zero—hence, a floating car. To conduct travel time trials, a 2002 Toyota Corolla was used. This vehicle was selected because it is ideal for urban travel within the study, not so large as to make being overtaken by other vehicles difficult and not so small as to allow it easily.

Travel time runs were conducted on two corridors within the study region: north from the intersection of SW 7 St. & SW D St. to NW 12 St. & NW G St., using SW 7 St. to NW Pennsylvania Ave., and south from the intersection of NW 11 St. & NW E St. to SW 7 St. & SW D St. via NW Pennsylvania Ave. to SW 7 St. Three trials were conducted for each corridor, from 4:00 pm to 6:00 pm.

To avoid human error, data were collected using a GPS travel recorder. Travel recorders measure time stamp latitude and longitude periodically. The model selected for this research was the Qstarz Travel Recorder BT-Q1000. This unit was selected because of its portability and accuracy. It has a hard drive capable of storing more than 300,000 data points and a built-in battery that allows 48 hours of continuous use without recharging. As the probe vehicle moved about the city, the GPS device captured latitude and longitude coordinates every five seconds. These points were later map-matched to check for accuracy, which was found to be superb.

Data Compiling and Time-Space Diagrams

After the travel time trials were completed, the information was downloaded using software provide by Travel Recorder Personal Computer Utility, Version 5. With this, the data were then "cleaned" by removing superfluous points made during collections (U-turns). The points were then grouped into individual trial, single trips north or south. Once completed, the information was exported from the GPS software into ArcGIS 9.3. Because the travel recorders capture only latitude, longitude, and time, the information was converted into feet for creating time-space diagrams.

Once the data points were plotted in ArcGIS 9.3 using World Coordinate System 1984, the points were then projected into the regional coordinate system of Washington, D.C. (Maryland state plane). Using the tools available, the state plane system can be translated into feet using north and south axes rather than longitude and latitude. This information was then exported into Microsoft Excel 2007 to produce time-space diagrams for comparison with the simulation. Time-space diagrams display cumulative distance on the Y-axis and time elapsed on the X-axis. From these figures, traffic engineers can begin to understand what vehicles are experiencing in the field. For the calibration of the developed network, time-space diagrams from the field were converted to time-space diagrams generated in the simulation.

Figures 4-8 and 4-9 show the results of the calibration for the north and south bounds, respectively. Outline in red are the time-space diagrams created from the GPS floating car trial. The black lines represent the time-space diagrams generated with the simulation environment. By matching these representative lines, the simulation model was calibrated.

Statistical Analysis

To compare the results of the calibrated model further, independent random samples of travel time were taken, both from the field and from the simulation environment. The field samples used for comparison are the three aforementioned floating car trial runs. The simulation sample was 10 randomly-selected travel time runs from the simulation model. To compare these data points, both populations must be normally distributed and both population (not samples) must

Figure 4-8

Northbound Route Time-Space Diagram

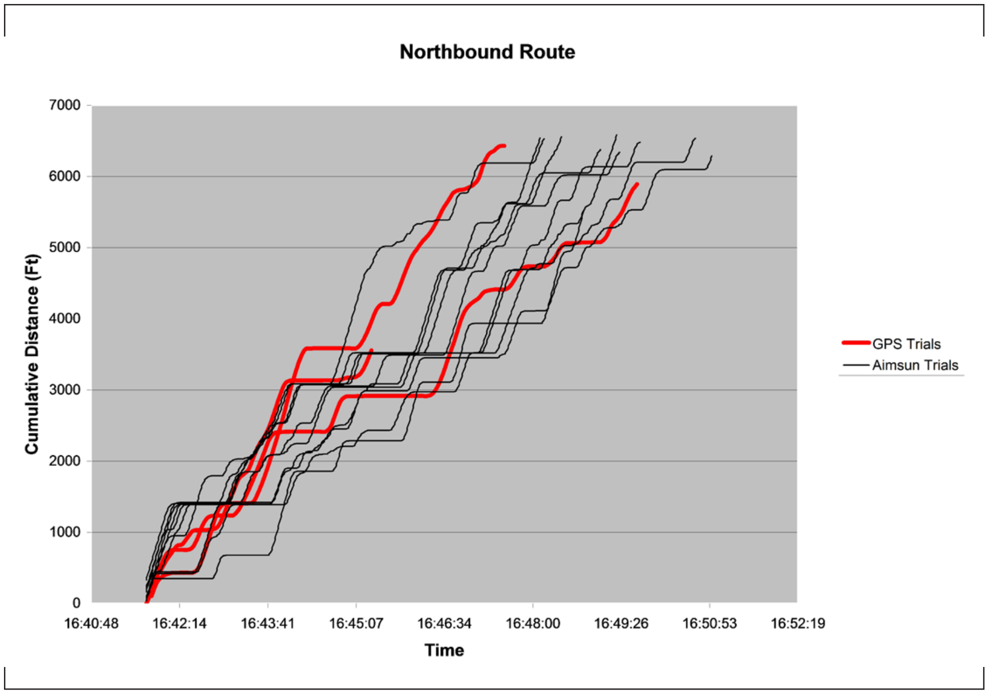
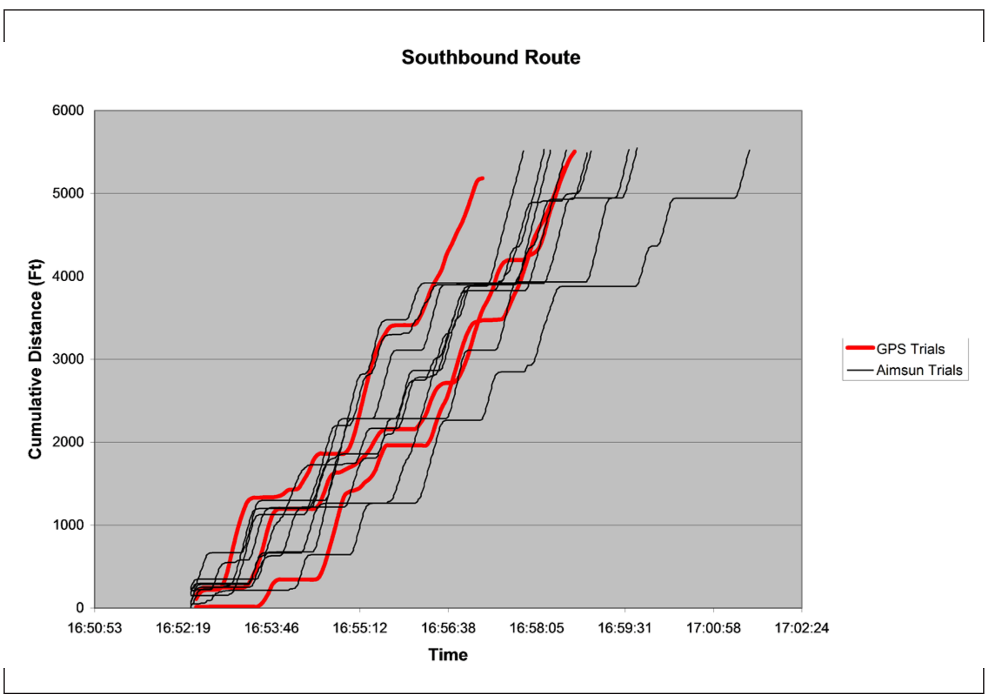


Figure 4-9

Southbound Route Time-Space Diagram



have the same standard deviation. Because the simulated sample was generated form a calibrated model, these assumptions hold.

For comparison of the random samples, a T-test was conducted. This test uses independent samples to make inferences about population means. For the purposes of this study, the T-test was used to verify the hypothesis that the population means are different within a predefined confidence level. The confidence level selected for this research is 95%. This confidence level states that repeated sampling will contain the same mean value μ for 95 independence trials out of 100. The southbound route used travel time information for the entire corridor. The northbound route, however, used only travel times for approximately the first 2,900 ft. Because of data corruption during time trial sampling, only the first 3,000 ft. of the northbound route were selected for the T-test. Using equations taken from Ott and Longnecker (2001), the T-test was conducted according Equations 28 and 29 in the Appendix. From sample quantities, the following information was found:

Northbound route:

$n_1 = 3$	$n_2 = 10$	$S_p = 43.36$
$\hat{Y}_1 = 155$	$\hat{Y}_2 = 184.5$	$\lvert t \rvert = 1.02$
$S_1 = 35$	$S_2 = 47.94$	$t_{a/2} = 2.201$

Southbound route:

$n_1 = 3$	$n_2 = 10$	$S_p = 43.36$
$\hat{Y}_1 = 333.33$	$\hat{Y}_2 = 379.7$	$\lvert t \rvert = 1.06$
$S_1 = 46.19$	$S_2 = 69.78$	$t_{a/2} = 2.201$

From this analysis, it is shown that we were unable to reject the hypothesis that our population means were different within a 95% confidence level. That is to say, it was impossible to statistically distinguish the field-observed travel times and the simulated travel times in 95 trials out of 100.

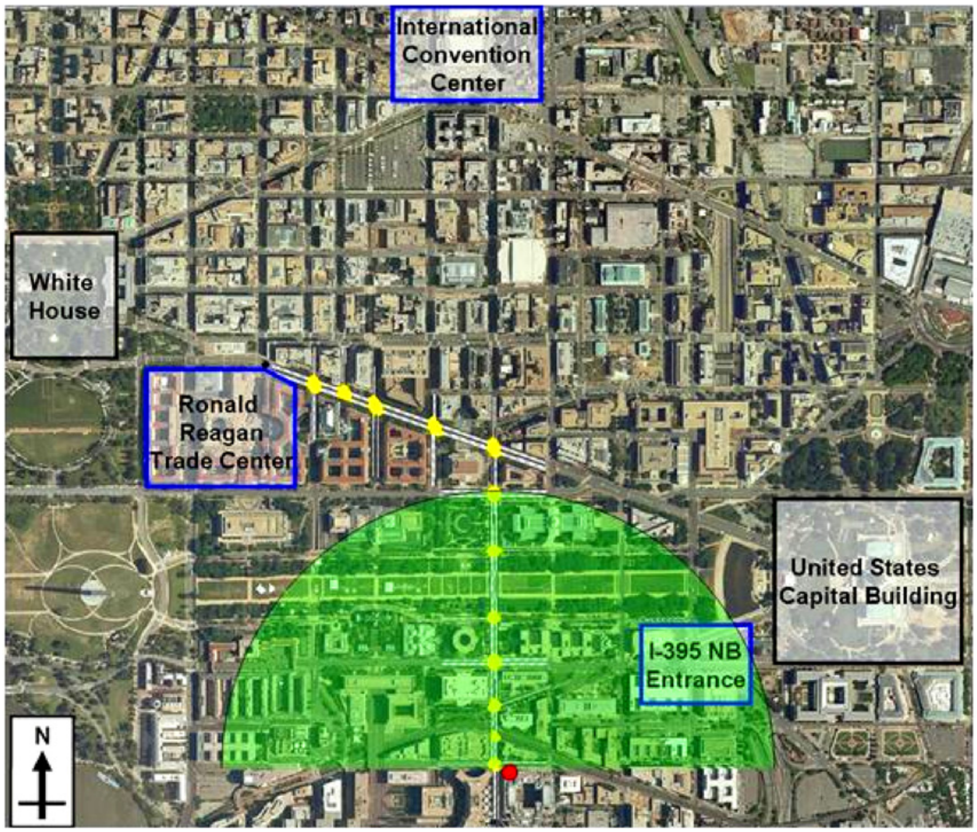
Evacuation Scenario

The terror attack is a dirty bomb explosion at the L'enfant Plaza Metro station (Figure 4-10). A dirty bomb is any explosive device that is surrounded by radioactive material; this material can be from spent fuel cells found at nuclear power plants or leftover material from a failed attempt at creating a nuclear bomb. The L'enfant Plaza Metro station connects four Metro lines (Blue, Green, Yellow, and Orange), making it a crucial interchange for commuters. A dirty bomb attack at this station could immediately kill hundreds while simultaneously disrupting the primary means of evacuating the radiological fallout. The evacuation from such an attack would be vital. Longer evacuation times resulting from the commuter disturbance at the Metro station will leave citizens exposed to the fallout longer and thus be more likely to suffer the effects (USNRC 2007). The lasting consequences would be devastating, rendering a portion of Washington, D.C. contaminated with fallout. This sort of attack would not be difficult to plan or carry out (USNRC 2007).

Figure 4-10 depicts the study area. Major landmarks are outlined in black for reference. The corridor is animated, with streets colored gray and intersections colored yellow. The explosion site is shown as a dark read circle, with the network-contributing evacuation semicircle colored green. Safe zones are outlined in blue, the International Convention Center to the north, the Ronald Reagan Trade Center to the west, and the entrance to I-395 northbound to the center east.

Figure 4-10

Emergency Scenario



The explosion takes place at 4:50 pm just as the PM peak period gets under way. This timing is ideal for terrorists because commuters will be arriving at the Metro station, thus increasing the casualties of the immediate explosion. The nearby traffic, already accumulating as a result of the time of day, is then saturated by evacuation traffic, causing gridlock and exposing people to fallout for longer periods of time while increasing the chances of serious injury or death.

As soon as it is realized (5:00 pm), decision makers give the order to evacuate the immediate area (a half-mile radius around L'enfant Plaza) and direct people to safe zones via radio and loudspeaker, where they can be examined and treated for radioactive exposure. Evacuees are directed away from the blast zone, where high concentrations of radioactivity are found. This results in populations to the south of the blast zone evacuating to the south, away from the study corridor, and areas to the north evacuate using the study corridor. Figure 4-10 displays this semicircle outlined in green. Because of the contaminated air and dust encompassing the region, police are directed to stay away from the area until hazardous material (hazmat) teams can provide them with the protective equipment (hazmat suits) needed. Any on-hand equipment is assumed to be used by medical personnel treating and transporting evacuees. This lack of vital resources means the evacuation will have to take place without police assistance at intersections. The entire region will have to evacuate using the signal timing plans specified in the District Response Plan: Transportation Annex.

Three safe zones are chosen—the International Convention Center to the north, the Ronald Reagan Trade Center to the west, and I-395 northbound to the east—where evacuees can seek assistance at other facilities further away. These safe zones are delineated blue in Figure 4-10. By 5:10 pm, it is assumed that commuter traffic (background demand) has become aware of the situation and begins to proceed out of the evacuating zones. By 5:20 pm, 30 minutes after the explosion, it is assumed that police, a safe distance away from the fallout, have closed all roads surrounding the evacuation area and treatment facilities. No additional background traffic will enter the study area from this point on. Additionally, at this time, the incident commander has called for additional resources (buses) to assist with the evacuation of non-terminal victims at the explosion site. Because the evacuation of this population is vital, any hazmat suits will be used by medical staff running the evacuation buses.

Origin-Destination Matrix

The O-D matrix was developed in accordance with the trip generation/distribution models described in the Methodology section. Each TAZ that resides within or touches the half-mile radius around the Metro station generates evacuation vehicles in accordance with the trip generation model. Because traveling through the fallout is not permitted, the only zones producing evacuation demand in this research are from zones located in the northern semi-circle of the radius. Variables Ei, Bi, Li, γi, Ui, Pi, Vi, are determined for the TAZ data collected from the area. Values for Ci,j and Cj,i are generated from the background traffic model and are time-dependent.

As a result of the dirty bomb, evacuees are directed to one of the three treatment areas: the International Convention Center, the Ronald Reagan Trade Center, or I-395 northbound. The International Convention Center is assigned a weight of attractiveness of 3 because of its size and perceived comfort. The Ronald Reagan Trade Center has a perceived attractiveness of 2 because it is smaller indoor area than that of the Convention Center. I-395 northbound is perceived to have an attractiveness of 1; this is due to the fact that people exposed to radiation need to be cleared by medical staff before returning home. Evacuees using I-395 are at a higher risk of suffering from the delayed effects of exposure;

therefore, this option is the least attractive. From these two models, an O-D matrix for all vehicles generated from the northern semi-circle as a result of the evacuation is formed (Table 4-1).

Table 4-1

Generated Evacuation O-D Matrix

TAZ	Convention Center	Trade Center	NB I-395	Total
28	194	218	53	465
68	407	434	465	1307
71	994	1065	3355	5414
72	231	208	238	678
73	556	487	417	1461
74	421	181	120	722
75	1684	1184	2946	5814
76	1663	1452	3253	6368
77	1431	1364	2790	5584
78	668	638	2125	3431
Total	8250	7231	15763	31244

Evacuation Route Choice

Using the Washington, D.C. network developed by Hess (2009) in Aimsun Professional version 6.0.5, the evacuation route choice methodology was applied to the case study. From this larger network, the Dijkstra algorithm has more links to choose the shortest path. Using ArcGIS 9.3, the center of each evacuation TAZ is located by area and entered into the simulation model as origins. The destinations for the safe zones are set to their commercial street address. Using the modified Dijkstra algorithm in Aimsun, the shortest path tree is created. Consequently, not all of the created paths travel using the study corridor. To simulate this, these O-D pairs are removed for the O-D matrix. The resulting matrix represents only vehicles that travel within the study corridor (Table 4-2). It is important to realize that the vehicles not represented in the O-D matrix exist on non-simulated paths that are equally congested during the event. Furthermore, as evacuation traffic and background traffic mesh within the simulation model, background traffic will re-route to correspond with evacuation traffic. Because these vehicles are also exposed to radioactive fallout, they, too, must seek a safe zone. The background traffic then joins the evacuation traffic and is distributed to one of the three treatment areas in accordance with the zone it is re-routed. For example, if background traffic generated from any zone travels into the evacuation area, that vehicle is redirected outward in accordance with the distribution model of the zone with which it was redirected in and not the zone with which it was generated.

Figure 4-11

Central Washington, D.C. Microsimulation Network

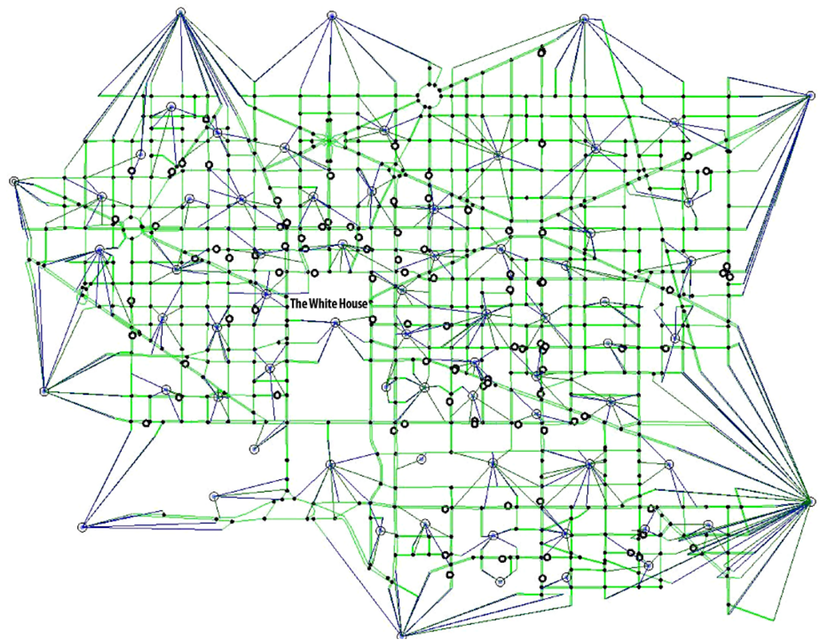


Table 4-2

Case Study Evacuation O-D Matrix

TAZ	Convention Center	Trade Center	NB I-395	Total
28	194	218	53	465
68	407	434	417	1259
71	994	1065	120	2179
72	231	208	0	440
73	556	487	0	1043
74	1431	181	0	1611
75	668	1184	0	1852
76	0	1452	0	1452
77	0	1364	0	1364
78	0	638	0	638
Total	4482	7231	591	12303

Test Strategies

The test strategies for the case study were developed in accordance with the evacuation scenario. Because police are unable to assist the evacuation traffic, the region is governed by the PM peak-hour signal-timing plan as specified by the District Response Plan: Emergency Transportation Annex. With that said, regional planners are left with a crucial decision: to allow buses transporting evacuees transit signal priority during the evacuation or not, the results of which may dictate who lives and who dies.

Before any strategies during an emergency can be conducted, the TSP logic must be tested on the PM peak-hour conditions within Washington, D.C. These results must lie within the range observed within the literature review so that any conclusions made for this research are shown to be valid. From here, three test strategies during the evacuation were conducted. The No Priority strategy is the evacuation using only the PM peak evacuation signal timing. The Priority strategy applies TSP to all bus lines within the study area. From the District Response Plan: Emergency Transportation Annex, these lines must continue service so long as the drivers do not travel though the fallout zone. These buses will be the primary means by which special needs populations, tourists, and commuters evacuate the region and thus need considerable attention. These buses will also consist of the hazmat-run emergency bus servicing lines 901 and 905 northbound from the explosion site to the Ronald Reagan Trade Center on westbound NW Pennsylvania Ave. The third strategy, Selected Priority, allows TSP only for lines 901 and 905 northbound serviced by hazmat officials. This strategy is designed to maximize the number of trips made by individual buses to minimize the amount of resources (buses and hazmat suits) required during the emergency. Furthermore, because the number of buses has an impact on TSP logic (reserve time), the number of additional buses used on lines 901 and 905 northbound will vary. The test scenarios during the evacuation for northbound lines 901 and 905 will have a combined headway of 20 minutes, 15 minutes, 10 minutes, 5 minutes, and 2 minutes. This results in 15 different possible combinations (3 strategies x 5 headways) in addition to the PM peak-hour scenario.

Results and Analysis

Using the simulation environment developed for the case study, 18 scenarios were tested (15 evacuation + 3 PM peak-hour scenarios). For accuracy of the results, each of the 18 scenarios was simulated 10 times and the results averaged, constituting 180 individual simulations runs totaling approximately 24 hours of non-stop data compiling. Furthermore, each scenario was looked at from the perspective of three different stakeholders: the transit evacuee not located at the site of the disaster (bus riders not using northbound lines 901 or 905), the transit evacuee located at the disaster site (riders of northbound lines 901 and 905), and the evacuee using a personal vehicle. For future reference, these stakeholders are noted as All Bus Routes, Selected Bus Routes, and Personal Vehicle, respectively. Each of these stakeholders has something to lose or gain by incorporating one of the three priority strategies being tested. The MOEs presented in this section are travel time and evacuation clearance time.

PM Peak Hour Results

The three test scenarios for the PM peak hour are No Priority, Priority, and Selected Priority. No Priority simple means no priority is given to transit vehicles. All intersections remain on the PM peak-hour signal-timing plan as received from DDOT. For this research, the No Priority scenario is used as the control for the calculations of the percent difference (% Dif.). The Priority scenario describes the case when all bus routes receive the same priority treatment at each intersection, the treatment being that TSP logic described in the methodology is applied to all transit vehicles at all intersections. The third scenario, Selected Priority, represent the case when the priority logic is applied only to northbound lines 901 and 905.

All Bus Routes

Table 4-3 displays the average travel time observed by bus riders on all lines except northbound 901 and 905. This table shows that when priority is granted to all transit lines, the average bus rider will experience a decrease in travel time of 16.86 percent. This value falls in line with other transit priority systems that use only green extension and red truncation strategies discussed in the literature review. This value when observed in the field ranged from a 9–35 percent reduction in travel time. This 14-intersection corridor has 17 lines traveling through it, which may account for the travel time reduction being on the lower end of the spectrum. When priority is given to selected routes only, an 8.32 percent reduction in travel time is observed by all bus routes, on average. Because many of the routes overlap within this relatively small corridor, any significant decrease in linked travel time is felt by multiple users. By allowing priority to northbound 901 and 905, a decrease in travel time is experienced by other buses traveling on the same street segment. This decrease is enough to decrease the average bus travel time by 8.32 percent.

Table 4-3

PM Peak-Hour Travel Time for All Bus Routes

All Bus Routes	PM Conditions	
Control Plan	***Time***	***% Dif.***
No Priority	186.66	
Priority	152.69	16.86
Selected Priority	168.38	8.32

Figure 4-12 plots the average travel time observed by all bus riders (with the exception of northbound 901 and 905) at 10-minute internals for the entire PM peak period. This graph shows that the 16.86 percent benefit realized by this population is consistent throughout the observation time. The benefit to bus users when selected priority is employed does not begin until almost 40 minutes into the PM peak period. At this time, the selected priority begins to decrease the travel time to bus routes other than its own.

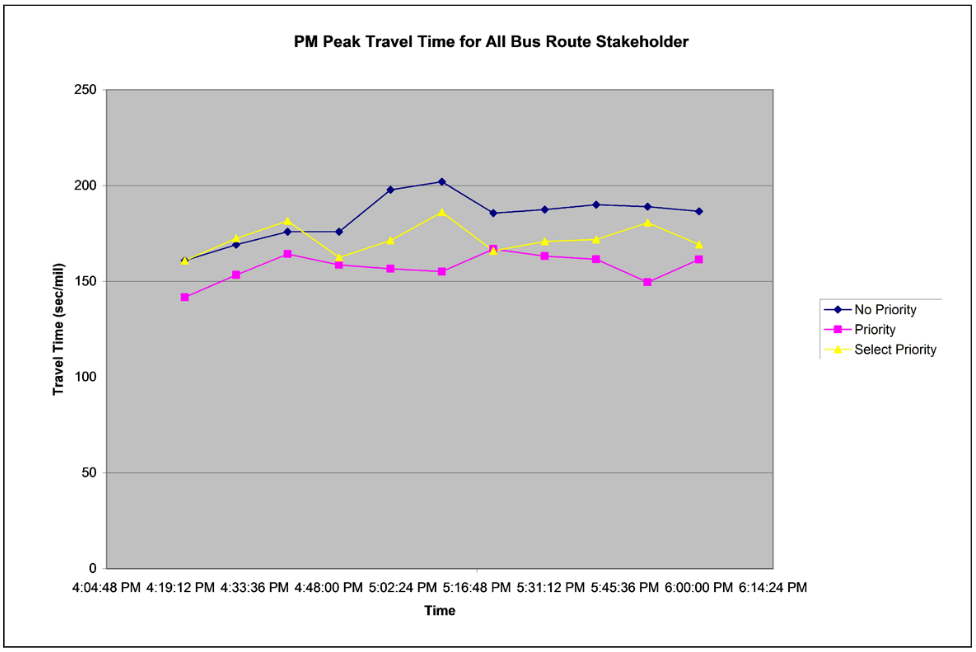


Figure 4-12

PM Peak Travel Time for All Bus Route Stakeholders

Selected Bus Routes

Table 4-4 displays the average travel time experienced by riders of the selected bus routes (northbound 901 and 905) during the PM peak. When priority is given to all buses, the selected routes see a decrease in travel time of 22.76 percent. This is due to the overlapping of many of the bus routes within the corridor. These overlapping segments receive priority requests from multiple transit vehicles and thus benefit accordingly. This number is in line with the 8.32 percent observed during Selected Priority experienced by non-priority transit units discussed in the previous section. When Selected Priority is given, the travel time decrease is 29.96 percent. By ridding the network of conflicting priority request, the selected lines experience an additional 9.2 percent reduction in average travel time.

Table 4-4

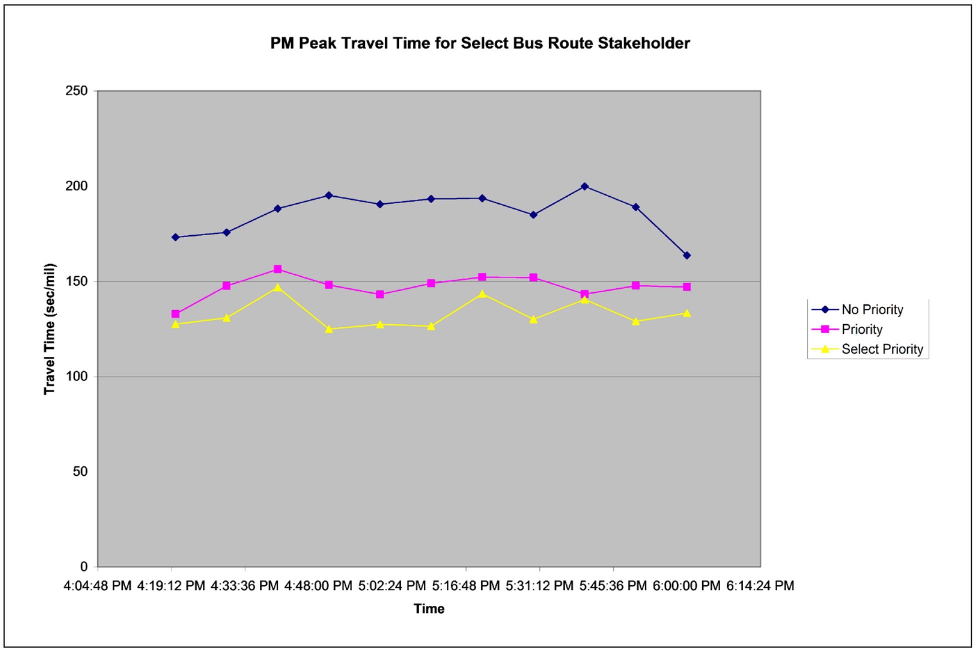
PM Peak-Hour Travel Time for Selected Bus Routes

Select Bus Routes	PM Conditions	
Control Plan	***Time***	***% Dif.***
No Priority	186.11	
Priority	143.75	22.76
Selected Priority	130.36	29.96

Figure 4-13 displays, from the perspective of individuals riding on selected routes (northbound 901 and 905), average travel time during the three priority strategies. This diagram illustrates the large travel time benefits for these routes when the signal priority logic is applied. The increased performance for these selected users when priority is given to all bus lines is the result of overlapping routes. This benefit is only furthered by restricting the priority to selected routes.

Figure 4-13

PM Peak Travel Time for Selected Bus Route Stakeholders



Personal Vehicles

Table 4-5 shows the average travel time for personal vehicles during the PM peak hour under the three priority strategies. An average travel time increase of 6.28 percent is experienced by personal vehicles when priority is granted to all bus routes. When the priority is restricted to a select few routes, this increase is reduced to 2.91 percent. Both these values are slightly high when compared to what practitioners see when using transit priority as researched in the literature review. This is due, in large part, to the unusual number of transit units within the study area and the particulars of the TSP logic. These increases are the result of additional red time experienced by side streets as a result of the priority.

Table 4-5

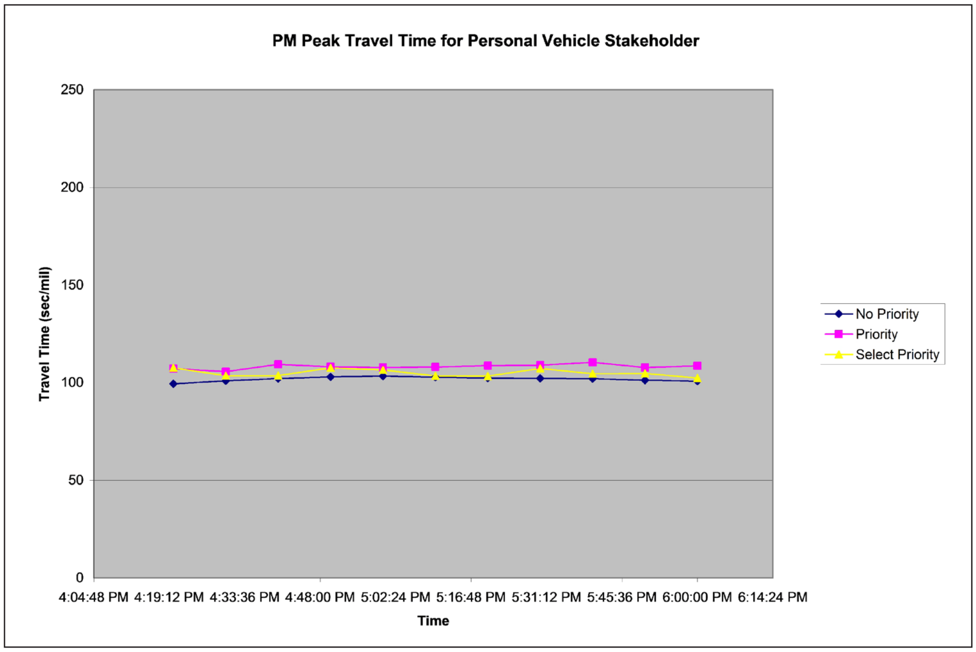
PM Peak-Hour Travel Time for Personal Vehicles

Select Bus Routes	PM Conditions	
Control Plan	***Time***	***% Dif.***
No Priority	101.56	
Priority	107.93	-6.28
Selected Priority	104.51	-2.91

Figure 4-14 depicts the average travel time for personal vehicles during the PM peak hour for the given priority strategies. Because the travel time fluctuation for personal vehicles between priority strategies is relatively small, the figure looks clustered. However, the No Priority travel time sticks out as having the lowest travel time, followed by the Selected Priority and the Priority strategies. Because personal vehicle travel times are much lower than those of transit vehicles, the 6.28 percent difference in travel time represents only an additional 6 seconds per mile.

Figure 4-14

PM Peak Travel Time for Personal Vehicle Stakeholders



Evacuation Results

The evacuation results in this section are shown using two MOEs: evacuation clearance time and average travel time. The average travel time is presented in two ways: average travel time tables, which constitute the averages over the entire simulation monitoring period from 4:20–10:00 pm and travel times for selected headways during the peak evacuation demand period. The peak demand period is taken to be 7:30–9:30 pm. This two-hour interval represents the time at which the most personal vehicles and transit vehicles are operating within the network. Because little variation was found between headways, only the five-minute headway for each stakeholder is presented here.

The most meaningful MOE in evacuation studies is clearance time. Clearance time is the time or duration required for the complete evacuation of a region. Table 4-6 displays the clearance time of each strategy for the given headway used for northbound 901 and 905 routes. The clearance time for this table is the first 10-minute internal during which no vehicles exit the network. This value ranges between 9:40 pm and 10:00 pm or 4 hours and 40 minutes to 5 hours after the evacuation order is given. The slightness of this range is a testament to the consistency of the simulation model. Regardless of the priority control plan used, the evacuation clearance time remains relatively unaffected. From this table, faintly lower clearance times are observed for the No Priority strategy, followed by Selected Priority and Priority. Furthermore, based on the information provided by this table, no conclusion can be drawn about the benefits or hindrances of the headway variations.

Table 4-6

Evacuation Clearance Time

Clearance Time	Evacuation Route Headway				
Control Plan	***20 Min***	***15 Min***	***10 Min***	***5 Min***	***2 Min***
No Priority	9:40 pm	9:40 pm	9:40 pm	9:40 pm	9:50 pm
Priority	10:00 pm	9:50 pm	9:50 pm	10:00 pm	10:00 pm
Selected Priority	9:50 pm	9:40 pm	9:50 pm	9:50 pm	9:40 pm

All Bus Routes

Table 4-7 displays the average travel time experienced by the All Bus Route stakeholders during the entire monitoring period (4:20–10:00 pm) for each headway of the northbound line 901 and 905. This table shows that riders of these buses experienced a decrease in evacuation travel time of about 26 percent consistently when priority was given to them, regardless of the adjusted headways of lines 901 and 905. When the Selected Priority control plan is employed, the bus travel time still decreases by around 23 percent, regardless of the headway scenario. This benefit is primarily realized by the buses that have overlapping street segments with those of routes 901 and 905.

Table 4-7

Evacuation Travel Time for All Bus Routes

Clearance Time	Evacuation Route Headway									
Control Plan	***20 Min***		***15 Min***		***10 Min***		***5 Min***		***2 Min***	
No Priority	*Time*	*%Dif*	*Time*	*%Dif*	*Time*	*%Dif*	*Time*	*%Dif*	*Time*	*%Dif*
No Priority	282.01		280.70		300.13		301.94		292.46	
Priority	208.47	26.08	212.95	24.14	218.07	27.34	223.90	25.84	213.80	26.90
Selected Priority	219.52	22.16	220.87	21.31	227.74	24.12	223.58	25.95	223.03	23.74

Figure 4-15 illustrates the average travel time witnessed by the All Bus Route stakeholders during the peak demand period of the evacuation when a five-minute headway is used for lines 901 and 905. This figure shows the benefits of transit priority during an evacuation. Without the priority, a significant portion of buses stuck on side streets are prevented from continuing on their routes. These buses experienced, during some instances, travel times nearing 1,400 seconds (23 minutes) per mile. Delays of this magnitude can leave transit-dependent populations stranded, with no other mode of transportation to deliver them from pending death. When the priority logic is used, traffic signals are forced to serve side streets, eventually alleviating the congestion that was preventing the passage of the transit vehicle. This pattern was consistent during all 150 simulated evacuation trials.

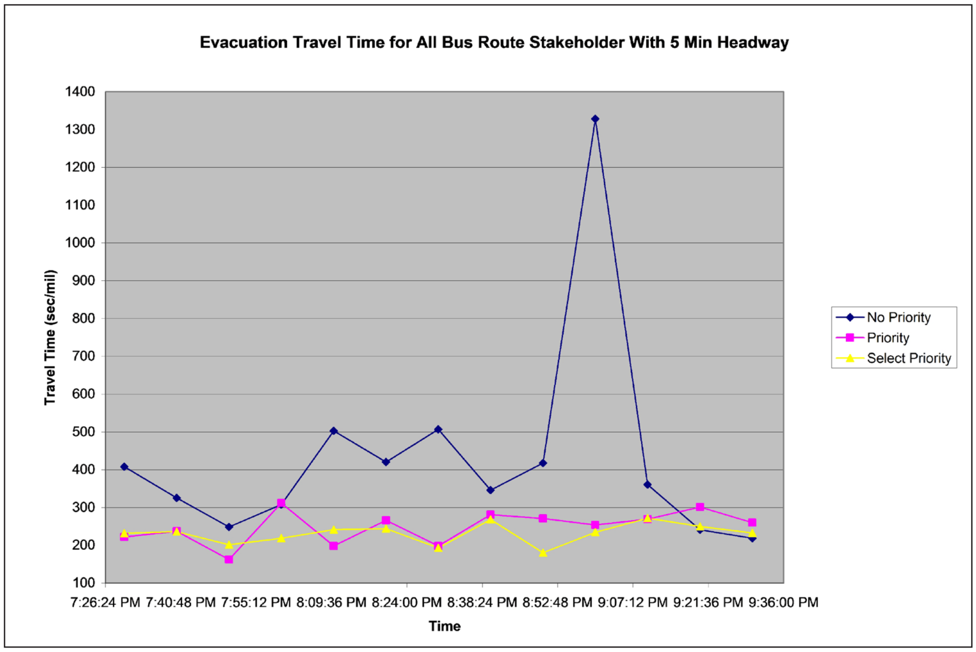


Figure 4-15

Peak Demand Travel Time for All Bus Routes with 5-Minute Headway

Selected Bus Routes

Table 4-8 illustrates the travel time experienced by the Selected Bus Route stakeholders during the entire evacuation for all three priority strategies. From this table, when priority is given to all buses, the selected bus routes benefit by about 7 percent, depending on the selected headway. When the priority logic is applied only to the selected routes, the travel time benefit increases to around 16 percent for the Selected Bus Route stakeholders. This is due to conflicting priorities requests. No conclusion can be made about the presence of additional headway on these routes. In some instances, the additional headway reduces the average travel time, and in others it increases it.

Table 4-8

Evacuation Travel Time for Selected Bus Routes

Clearance Time	Evacuation Route Headway									
Control Plan	*20 Min*		*15 Min*		*10 Min*		*5 Min*		*2 Min*	
No Priority	*Time*	*%Dif*	*Time*	*%Dif*	*Time*	*%Dif*	*Time*	*%Dif*	*Time*	*%Dif*
No Priority	244.10		255.55		270.29		280.71		290.40	
Priority	223.82	8.31	246.49	3.54	251.58	6.92	253.88	9.56	262.70	9.54
Selected Priority	218.84	10.35	208.35	18.47	227.26	15.92	228.36	18.65	247.79	14.67

Figure 4-16 shows the travel time experienced by the Selected Bus Route stakeholders during the peak evacuation demand period with a five-minute headway. This figure exemplifies the benefits realized by the selected routes buses during the priority. Even during complete network saturation, priority is able assist these travel time. With this kind of travel time reduction during the peak demand period, these units are able to make more trips to and from the site of the disaster.

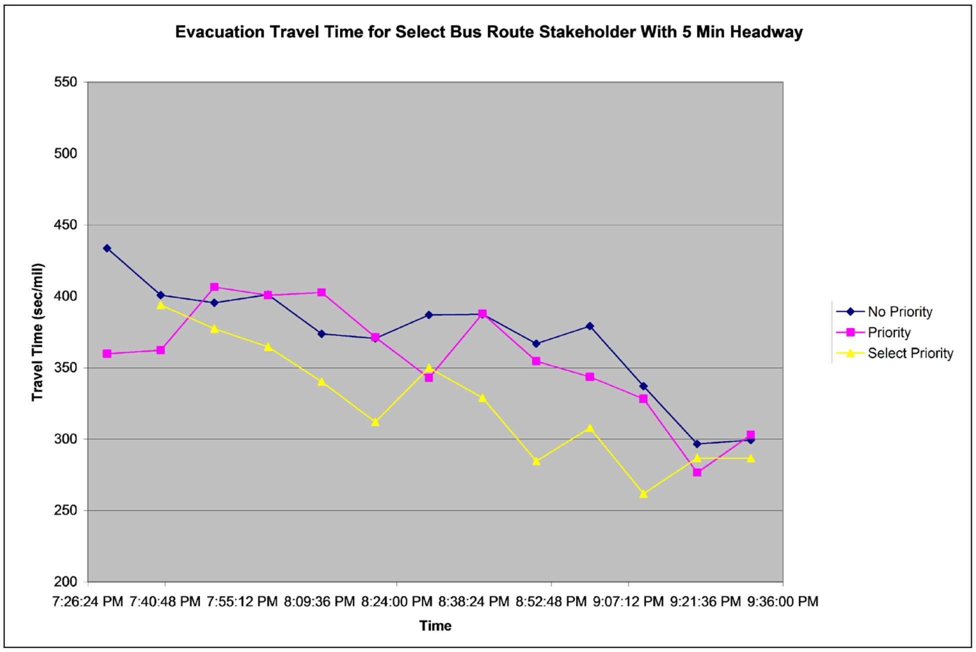


Figure 4-16

Peak Demand Travel Time for Selected Bus Route with 5-Minute Headway

Personal Vehicles

Table 4-9 shows the effect the three priority strategies have on the travel time of the Personal Vehicle evacuee. The Personal Vehicle evacuee has an average travel time of approximately 8 minutes and 40 seconds per mile using the PM peak-hour signal controls. When priority is given to all transit vehicles, little change is observed in average travel time. When priority is given to selected bus routes, the average travel time for personal vehicles decreases by about 8 percent for 20-minute, 15-minute, 10-minute and 5-minute headways. Because these selected routes correspond to the street sections that are in the highest demand, the benefits are observed by all users of this segment, not just transit vehicles. When selected routes operate on 2-minute headways, this benefit increases to an almost 15 percent reduction in travel time. This is due to more priority requests being generated by the additional transit vehicles associated with a 2-minute headway.

Table 4-9

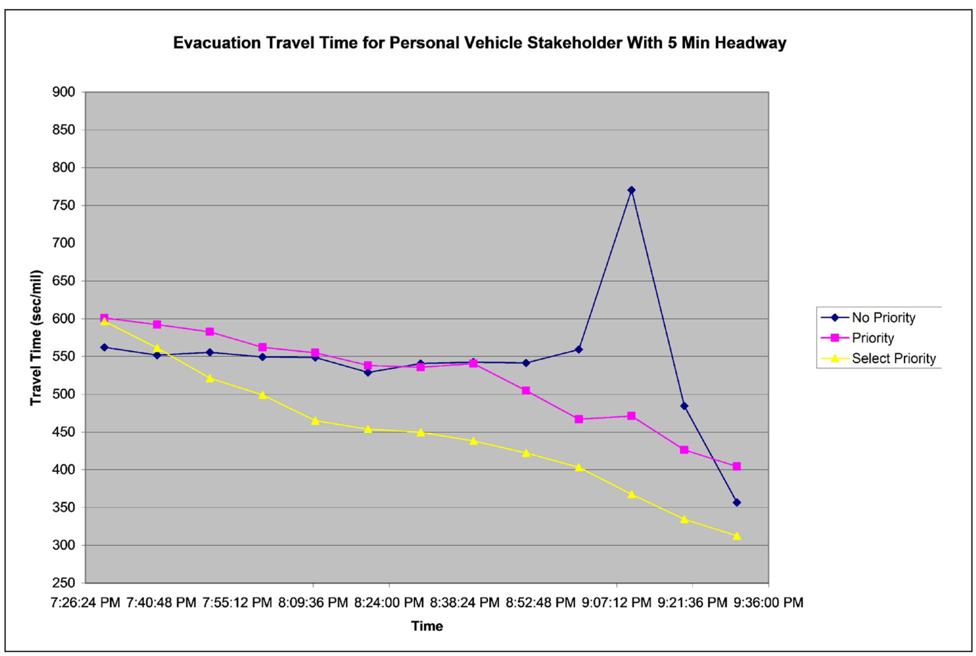
Evacuation Travel Time for Personal Vehicles

Clearance Time	Evacuation Route Headway									
Control Plan	20 Min		15 Min		10 Min		5 Min		2 Min	
No Priority	Time	%Dif	Time	%Dif	Time	%Dif	Time	%Dif	Time	%Dif
No Priority	512.62		512.87		512.85		506.46		546.81	
Priority	507.36	1.03	509.66	0.63	515.71	-0.56	521.15	-2.9	503.50	7.92
Selected Priority	467.88	8.73	472.60	7.85	470.13	8.33	470.34	7.13	466.53	14.68

Figure 4-17 shows the travel time witnessed by personal vehicles during the peak demand period for a five-minute headway. This graph show that when no priority is given, vehicles generated on side streets experience travel times as high as 13 minutes per mile. When priority strategies are employed, these streets are able to discharge their queue regularly, instead of holding the queue until the main street is cleared of traffic. Even in cases where the side street is not located on a bus route, the increase in the main street level of service allows more opportunity for vehicles on side streets to turn onto the main street. Furthermore, the priority on the main street shortens the main street queue length, which otherwise grows so extensively that it blocks the downstream intersection during the green phase for side streets, preventing the thru and left-hand turn movements of the side street.

Figure 4-17

Peak Demand Travel Time for Personal Vehicles with 5-Minute Headway



After reviewing the results, it can be seen that allowing TSP during an emergency evacuation has a significant benefit to transit units. Even in cases where only selected routes have priority, transit traffic in general experiences benefits in the form of travel/delay time reduction and increases in average speed. Furthermore, allowing priority to all bus lines has little to no effect on personal vehicle evacuation traffic. When priority is granted to selected routes that correspond to evacuation routes, significant travel time savings are witnessed by personal vehicles traveling on evacuation routes. This is due to the sharing of road segments between these modes and associated benefits of increasing the level of service on main streets.

SECTION 5

Conclusions

Case Study 1 presented a method of using two transportation modes for evacuation by allowing passenger cars and public buses to evacuate the area surrounding an emergency. The model takes into account individual independent choices while using real traffic data with a meso-simulation process to evacuate the area in an efficient and streamlined manner. This method could easily be included in the existing evacuation plans of Washington, D.C. in case of a similar situation.

Future work following this research will focus on a more dynamic scenario by designing a method to create more realistic conditions of the evacuation method with real-time adjustments of the input data. This will allow for more accurate simulations and results that can be incorporated into this method. Continuing work will also focus on expanding the network to include evacuation plans that can be incorporated with additional Metro stations and TAZs throughout the entire city and surrounding areas. In addition, there will be a focus on how to evacuate populations with special needs.

Case Study 2 effectively addressed the optimal allocation of bus stops for the purpose of evacuating special needs populations. The proposed methodology was 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 was 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 were 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 needs 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 needs 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 using 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 TAZs through a spatial aggregation process and specifying the minimum number of bus stops per TAZ group can aid in overcoming clustering of optimum bus stop locations and provide a more even 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 large travel, delay, and stop times because of the diverse spread of resources and the 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 number of bus stop locations gave a superior performance. 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 times with the best spatial spread of evacuation bus stops.

Recommendations if this work was to be furthered include devising 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 developing further grouping of TAZs 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 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 collected 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 act 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.

From Case Study 3, transit signal priority during the evacuation of an urban area ws shown to have little to no interference with evacuation clearance time or non-transit evacuee travel time. Even in case where bus headway was set to two minutes or an "as soon as possible" approach, non-transit evacuees experienced no significant changes in travel, delay or speed times when transit signal priority was granted to all vehicles. Moreover, when priority was given to transit vehicles with routes corresponding to evacuation routes, non-transit evacuees experienced a decrease in travel and delay times while enjoying an increase in speed and subsequent level of service. The level and extent of this is dependent upon the headway of these vehicles: the higher transit vehicle frequency (shorter headways), the more non-transit vehicles benefit.

Furthermore, by allowing transit vehicles priority during the evacuation, a 26 percent time saving was attributed to transit units. This signifies that three prioritized buses can do the work of four non-prioritized buses. This savings is then translated into additional trips being made by transit units. More trips means shorter evacuation times, smaller delays in treatment for injured populations, and ultimately fewer deaths caused by a disaster. With this said, the use of transit signal priority is recommended during an urban emergency evacuations when police-assisted traffic controls are not an option. With the use of the methodology explained here, TSP was found to have little significant impact on evacuation traffic. However, granting the TSP only on evacuation routes reduces personal vehicle travel time and, thus, is a more appropriate course of action to take.

Future work in the field of evacuation planning is limitless. As for research in the field of transit signal priority during evacuation, testing of additional priority logics, not simply a green extension and red truncation approach, is an area that can significantly affect the recommendations made by this research. Other priority logic systems in place could have significantly different results than the ones observed here. Furthermore, the size and scope of the study area could be expanded to incorporate more street segments and transit bus lines. This expansion would increase the number of priority requests being generated within the evacuation area and, thus, may highlight areas of improvement. Once again, further work is needed in the field of traffic control modeling and police-assisted traffic control. During no time while conducting the literature review was an accurate and reliable method of emulating police officers at intersections in microscopic simulation found. By studying the habits of officers controlling event traffic and the responses of drivers during such situations, microscopic simulations could be develop in such a way that police and driver interactions during an extreme saturation occurrence can be more accurate and representative of a traffic environment.

APPENDIX

Equations

Case Study 2

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Subject to:

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

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

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

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

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

$$N_z^{max} = \begin{cases} \frac{A_z}{A_b^{max}} & if \ \frac{A_z}{A_b^{max}} \geq \frac{T_z}{T_b^{max}} \\ \frac{T_z}{T_b^{max}} & otherwise \end{cases} \tag{21}$$

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

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 who do not own a vehicle
e = persons over age 65
l = person with a low income (below poverty line)
s = persons with physical disabilities
y = employees
w= weight defined by the decision maker to a criteria category
p = size of special needs population
T = bus trips required to evacuate special needs population
A = area
ξ = minimum N^{max} value necessary to have a bus stop
η = maximum total number of bus stops for the entire study area

$$N_{23}^{max} = 3 \tag{23}$$
$$N_{10}^{max} + N_{11}^{max} + N_{12}^{max} + N_{13}^{max} \geq 1$$

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

Where,

g = group of TAZ that fall into a grid cell

ε_g = minimum number of bus stops in each TAZ group g

Case Study 3

$$G_i = E_i B_i \left(1 - \frac{L_i}{2} - \frac{\gamma_i}{3.5}\right) + U_i P_i (1 - V_i) + \sum_{t=0}^{T} \sum_{j=1}^{J} C_{j,i} - \sum_{t=0}^{T} \sum_{j=1}^{J} C_{i,t} \tag{25}$$

Where,

G_i = generated vehicles from zone i

E_i = number of employees in zone i

B_i = ratio of commuter employees to transit riders

L_i = ratio of two carpoolers per vehicle to all commuters in i

γ_i = ratio of three or more carpoolers per vehicles in i

U_i = unemployment rate of i

P_i = residential population of i

V_i = ratio of residents whom do not own vehicles in i

$C_{i,j}$ = vehicles departing i to j at time t

The first term in Equation 25 represents all commuting employees within zone i. The second term accounts for all remaining residents within zone i who possess vehicles. The third term accounts for all vehicles from the background generation demand model entering zone i at time t. The fourth term removes any vehicle generated from the background model that has already vacated the area by time t.

$$p_{i,j} = \frac{W_j \frac{1}{d_{i,j}}}{\sum_{j=1}^{J} W_j \frac{1}{d_{i,j}}} \quad \forall\, i,j \tag{26}$$

$$\varepsilon_{i,j} = \rho_{i,j} G_i \quad \forall\, i,j \tag{27}$$

Where,

$p_{i,j}$ = probability of an evacuee in zone i selecting j as a safe zone

W_j = perceived desirability of j as a safe zone

$d_{i,j}$ = travel distance between zone i and j

$\varepsilon_{i,j}$ = Number of vehicles leaving zone i for j

This equation distributes the produced vehicles for the trip generation model to safe zones in accordance with the safe-zone probability model. From this, an O-D matrix is constructed by aligning the evacuation zones as rows and the safe zones as columns. Each matrix cell holds the value of $\varepsilon_{i,j}$. The number of vehicles produced from zone i, destined to zone j.

H_0:

$$\mu_1 - \mu_2 \leq D_0$$
$$\mu_1 - \mu_2 \geq D_0$$
$$\mu_1 - \mu_2 = D_0$$

H_α:

$$\mu_1 - \mu_2 < D_0$$
$$\mu_1 - \mu_2 > D_0$$
$$\mu_1 - \mu_2 \neq D_0$$

$$S_p = \sqrt{\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2}} \tag{28}$$

T.S.: (29)

$$t = \frac{(\overline{Y}_1 - \overline{Y}_2) - D_0}{S_p\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}}$$

1. Reject $H_0\ if\ t \geq t$
2. Reject $H_0\ if\ t \leq -t$
3. Reject $H_0\ if\ |t| \geq t_{\alpha/2}$

Where,

μ_1 = mean of population 1
μ_2 = mean of population 2
D_0 = specified value, often taken to be 0
S_p = estimate for common standard deviation
n_1 = number of samples taken from population 1
n_2 =number of sample taken from population 2
s_1 = standard deviation of sample 1
s_2 = standard deviation of sample 2
t = test statistic
$\overline{Y}_1$ = mean value of sample 1
$\overline{Y}_2$ = mean value of sample 2
$t_{\alpha/2}$ = test statistic threshold for confidence level α

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