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Evaluating the Suitability of Phased Evacuation and Contraflow for the Evacuation of Boston's Coastal Population

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EVALUATING THE VIABILITY OF PHASED EVACUATION AND CONTRAFLOW FOR BOSTON'S COASTAL POPULATION

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DEDICATION

This thesis is dedicated to my dad, mom, and sister who were always available to listen, critique, and encourage me throughout this grueling, yet rewarding journey.

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"A man's gift makes room for him and brings him before great men." Proverbs 18:16. First, may all the praise and glory be to my Lord Jesus Christ. For He is faithful.

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ABSTRACT

Because the city of Boston rests along the Atlantic coast and is highly vulnerable to flooding from hurricanes, local emergency planners have considered utilizing phased evacuation and contraflow strategies as a means to more effectively evacuate. This research attempted to determine whether phased evacuation or contraflow are suitable evacuation strategies that can be incorporated into Boston's evacuation plan in order to increase the evacuation rate and reduce motor vehicle congestion throughout an evacuation.

A computer simulation evaluating the use and non-use of phased evacuation and contraflow was performed. The simulated evacuation included 50% of the population from South Boston and the Columbia Point peninsula of Dorchester and a 20% shadow evacuation from downtown Boston. This research concludes that when an evacuation anticipates moving 60,000 vehicles or less from coastal areas, contraflow may not be necessary, while phased evacuation will require thorough planning prior to implementation to avoid extending an evacuation beyond the scheduled timeframe.

TABLE OF CONTENTS

LIST OF FIGURES

Chapter I

Introduction

"Over the past 40 years, there has been an explosion of population growth along the Atlantic and Gulf coasts; the population of coastal counties in Maine down to Texas exceeds 45 million alone. Despite this growth, the number of evacuation routes has remained relatively unchanged over the past few decades" (Wolshon, Urbina, & Levitan, 2001, p. 5). In 2004, Hurricane Ivan resulted in the evacuation of millions of coastal residents from Florida, Alabama, Mississippi, and Louisiana; more than 200,000 vehicles made their way across Louisiana with a wait time up to 24 hours (Wolshon, Catarella-Michel, & Lambert, 2006, p. 2). Trips of 80 miles from New Orleans to Baton Rouge exceeded 8 hours (Wolshon et al., 2006, p. 2). Portions of Interstate 10 were severely damaged, with a quarter mile section of the bridge collapsed; U.S. Highway 90 Causeway was also heavily damaged (NOAA, 2005). This lumbering hurricane showered an accumulated 3-7 inches of rain, which spanned from New Hampshire to the east coast of Florida; a storm surge of 10-15 feet; and an outbreak of 117 tornadoes over a three-day period in the U.S (NOAA, 2005). Ultimately, 25 deaths were reported in the U.S.

Over the past few decades, this nation has witnessed the vulnerability of coastal populations, whether in the Atlantic or Gulf coasts, to the tremendous power of hurricanes and their frightening aftermath. Superstorm Sandy, a worst-case scenario for many of the affected states, is among the most recent examples that illustrates the coastal vulnerability of the eastern seaboard. (See Appendix A for picture, NOAA, 2012). As Sandy moved up the east coast, prior to making landfall in Atlantic City, New Jersey on

October 29, 2012, it sent "powerful waves onto North Carolina's Outer Banks, washing out NC Highway in 12 places" (Drye, 2012, p. 5). Ultimately, Superstorm Sandy's winds that stretched 1,000 miles, with gusts up to 80 miles per hour, and storm surges that reached up to 12 feet in height, affected 50 million people on the eastern seaboard, killing 70 people in the Caribbean and 109 in the United States (Drye, 2012, p. 6). The primary method of escaping these devastating monsters is to evacuate the threatened area.

However, as Hurricane Ivan revealed, the process of evacuating can become a complex and time-consuming problem. This paper describes and evaluates the effectiveness of two evacuation strategies known as phased evacuation and contraflow and their ability to improve evacuations. As these strategies have not been applied to Boston's evacuation plan, this paper will utilize the Real Time Evacuation Planning Model (RtePM – pronounced "Route-PM") as a baseline to explore this research goal.

The purpose of this evaluation is to determine whether phased evacuation or contraflow would improve evacuation from the coastal areas of South Boston and the Columbia Point peninsula of Dorchester by reducing motor vehicle congestion. The literature review will explore the following questions: (a) is Boston located in a high-risk area that necessitates the implementation of these strategies? (b) are traditional evacuations effective? (c) how do these strategies improve evacuations? and (d) what are the known benefits and obstacles?

Chapter II

Literature Review

Hurricane Activity in New England

The city of Boston is located in the state of Massachusetts, which is one of six states that are known collectively as New England. In addition to Massachusetts, New England is comprised of Maine, Vermont, New Hampshire, Rhode Island, and Connecticut. According to the National Weather Service's New England Hurricane Statistics (2005), a total of "49 Tropical Cyclones have impacted the region since 1900 – 25 Hurricanes and 18 Tropical Storms: The 1938 Hurricane caused severe flooding from 13 to 17 inches of rain in central Connecticut and western Massachusetts; 9 hurricanes made landfall on the coast, with four being Category 3 intensity [sustained winds of 111-130 miles per hour (mph)], and storm surges ranging from 8-12 feet along the south coast." Other notable, destructive hurricanes in this centennial review included Hurricanes Carol and Edna 1954, Categories 2 and 3; and Hurricane Bob 1991, Category 3 (Commonwealth of Massachusetts, 2010).

While New England has had a long history of hurricane activity, Glenn Fields, a Warning and Notification Coordinator at the National Weather Service, explains the risks associated specifically with the Boston harbor region. "There are three primary characteristics associated with hurricanes affecting this region: (1) Rapid acceleration up the coast—average forward motion is 33 mph; (2) sustained tropical (36-73 mph) and hurricane force (74 mph or greater) winds present 12 hours before landfall, with the strongest felt at 3-6 hours; and (3) coastal inundation due to storm surges that range from

5-7 feet, accumulated rainfall up to 17 inches, and significant river and small stream flooding" (personal communication, April 8, 2010). A centennial review of hurricanes affecting the New England area, and interviews of meteorologists for the National Weather Service, both agree that Boston harbor is a high-risk area for tropical storms and hurricanes reaching up to Category 3 intensity.

Traditional Evacuation

When faced with an approaching hurricane, the primary method of escaping their impact is to evacuate. Issuing either a voluntary, recommended, or mandatory evacuation initiates an evacuation. Evacuees will either follow established evacuation routes, which may only be signs identifying the routes out of town, or they will take what they believe is the quickest route to their destination. With traditional evacuations, there are no mandatory routes that direct people out and away from the threatened area(s), nor are there methods by which to control and coordinate the massive surge of people wanting to evacuate. The following review of Hurricanes Georges, Floyd, and Rita, with an extended analysis of Hurricane Ivan, will show the effects of a traditional evacuation.

As previously mentioned, Hurricane Ivan resulted in extensive wait times and miles of roadway congestion. Journal of Transportation Engineering authors' Wolshon et al. (2006) note "conditions in Baton Rouge reached jam density back as far as 20 miles from the Mississippi River Bridge on I-10, I-12, and US-61 for approximately 26 hours" (p. 3). Wolshon et al. (2006) further explain "[s]ince the threat area was largely to the east of the city, daily activities and traffic patterns in Baton Rouge continued in their normal routines, with local commuter traffic using the prime evacuation routes.

Conversely, evacuation traffic seeking to avoid congested freeways began to shift to the local primary arterial road system, thereby making trips within the city of Baton Rouge a challenge" (p. 3). It should be noted that Louisiana did implement a contraflow plan, however, Keifer and Montjoy (2006) explain, "Hurricane Ivan was the first time this plan had been implemented. Some of the reasons why it was considered a failure included a lack of coordination among neighboring parishes and serious bottlenecks, such as the junction of Interstates 10 and 55. The normal commute of less than two hours from New Orleans to Baton Rouge increased to 14 hours" (p. 125). Ultimately, the poor manner in which contraflow was designed and implemented during Hurricane Ivan led to serious congestion. Further discussion of contraflow will be explored later.

Hurricane Rita, making landfall at the border of Texas and Louisiana in 2005, brought accumulated rainfall exceeding 6 inches; storm surges ranging from 8-15 feet; sustained winds of 120 mph, reaching 150 miles inland; and resulted in an evacuation of nearly 3 million residents from Louisiana and Texas (NOAA, 2005). This massive evacuation created colossal 100-mile-long traffic jams that left many stranded and out of fuel (Litman, 2006, p. 13). Author Todd Litman (2006) offers an interesting detail noting "[o]fficials […] made matters worse by announcing at one point that they would use inbound lanes on one highway to ease the outbound crush, only to abort the plan later, saying it was impractical. […] As congestion worsened, state officials [again] announced that contraflow lanes would be established on I-45, U.S. 290, and I-10. But by mid-afternoon, with traffic immobile on U.S. 290, the plan was dropped, stranding many and prompting others to reverse course" (p. 13). After reviewing lessons learned from Katrina and Rita, Litman (2006) concludes that many of the transportation issues were a combination of failures including "failure to implement contraflow lanes as announced, failure to manage fuel distribution, failure to provide basic services (such as washrooms) along the evacuation route, and failure to give buses priority in traffic" (pp. 16-17).

While contraflow was tested during Ivan and considered during Rita, the original event that prompted consideration of such a strategy was during Hurricane Georges in 1998 and Hurricane Floyd in 1999. The National Review of Hurricane Evacuation Plans and Policies (2001), developed by the LSU Hurricane Center, reports the "Georges and Floyd experiences clearly demonstrated the need for increased evacuation route capacity; development of systems for better, faster, more reliable exchange of traffic flow and traveler information; and better planning and coordination of regional and cross-state evacuations" (Wolshon, Urbina, & Levitan, 2001, p. 3). This perspective is also shared by other academics. Keifer and Montjoy (2006) claim the "impetus for the [Louisiana] contraflow plan came from Hurricane Georges in 1998, when evacuees sat in unmoving lanes on Interstate 10 while looking at empty lanes heading back into the city. Additionally, Wolshon et al. (2006) explains "the I-10 contraflow plan was developed in 2000, in the wake of Hurricane Georges in 1998 and the increased acceptance of contraflow as a viable tool in other states following Hurricane Floyd in 1999" (p. 2).

Hurricane Georges of 1998 brought winds averaging 90 mph, severe flooding from 18-30 inches of rain, and storm surges at or above 14 feet, resulting in the devastation of part of Interstate 10 and mandatory evacuation of 250,000 Florida residents (NOAA, 1999). One year later, Hurricane Floyd arrived with much more devastation, despite being rated Category 2, one level lower than Hurricane Georges.

Floyd brought an accumulated 19 inches of rain and storm surges reaching 10 feet, flooding most roads east of I-95 and initiating an evacuation of approximately 2.6 million people from Florida, Georgia, and the Carolinas—at the time, this was the largest peacetime evacuation in U.S. history (NOAA, 1999). According to Dow and Cutter (2002), "As a result of [Floyd's] trajectory, Florida and Georgia evacuees heading north along I-95, which parallels the coast, were met by evacuees from coastal South Carolina evacuating west and north. In South Carolina, this evacuation resulted in a lengthy traffic jam on I-26 westbound out of Charleston and the implementation of an unplanned lane reversal along a 161 km segment of I-26 to Columbia. Despite this radical alteration in plans, some evacuees still experienced a ten-fold increase in normal travel times […]" (p. 12).

Each coastal hurricane discussed above, whether Hurricane Ivan, Rita, Georges, or Floyd, has one important element in common—a lack of an adequate system to control and coordinate evacuation in order to minimize vehicle congestion and decrease evacuation time. Based on the mentioned case examples, illustrating the effects of limited direction or control of evacuees, Boston is also at risk by not having a plan to coordinate their evacuees. However, in contrast to traditional evacuations, two alternatives, known as phased evacuation and contraflow, have been shown to improve both vehicle congestion and evacuation time. The following section will include (a) a discussion of how these alternatives function, (b) how they improve evacuations, and (c) their benefits and obstacles. Contraflow will be discussed first, followed by phased evacuation.

Contraflow Evacuation

Prior to discussing the methods of increasing evacuation rates, it is important to understand that roadway capacity is a predetermined capacity and cannot be changed. "According to the Transportation Research Board's Highway Capacity Manual, a roadway's capacity is defined as 'the maximum hourly rate at which persons or vehicles can reasonably be expected to traverse a point of uniform section of lane or roadway during a given time period under prevailing roadway, traffic and control conditions'" (I-495 Study, 2009, p. 5). Though the maximum rate cannot be changed per lane, it can be increased by adding lanes; hence the reasoning for contraflow as a means of improving evacuation rates. In agreement with this reasoning, Brian Wolshon (2006) affirms "transportation infrastructure is neither planned nor designed to accommodate evacuation-level demand; building enough capacity to move the population of an entire city in a matter of hours is simply not economically, environmentally, or socially feasible" (p. 28).

"Contraflow, or reverse laning as it is also commonly known, involves the reversal of traffic flow in one or more of the inbound lanes (or shoulders) for use in the outbound direction with the goal of increasing capacity" (Wolshon et al., 2001, p. 20). Author Brian Wolshon (2001) explains "[c]ontraflow operations on roadways is not a new concept. […] Contraflow operation is common on bridges where one or more outbound lanes are used for inbound commuters during the morning rush hour and one or more inbound lanes are used for outbound traffic during the evening peak hours" (p. 105). Depending on geography, transportation infrastructure, and shelter locations, one of four different contraflow designs can be implemented. These designs include “normal operation, normal plus one contraflow lane, normal with shoulder and one contraflow lane, and normal plus two contraflow lanes” (Wolshon, 2001, p. 106). Four lanes of contraflow, known as “one-way-out”, will provide the highest increase in outbound capacity, and is therefore considered to be the most strategic configuration (Wolshon, 2001, p. 106). This can be illustrated by the following estimation of the average flow rate (vehicles per hour) for each contraflow design: Normal (two-lanes outbound) = 3,000 v/h, normal plus one contraflow lane = 3,900 v/h, normal and shoulder plus one contraflow lane = 4,200 v/h, and normal plus two contraflow lanes = 5,000 v/h (Wolshon, B., 2001, p. 107, as cited in FEMA, 2000). As the above estimation illustrates, one contraflow lane improves evacuation rates by 30%, while full lane reversal can increase evacuation rates by nearly 70%. The benefits of such an increase in the rate of flow were seen during Katrina and Rita (in Texas), and computer simulations of North Carolina’s contraflow plan for I-40 and the Martin Luther King (MLK) intersection.

According to NOAA (2005), “Both of New Orleans’ airports were flooded and closed by August 30th and bridges of I-10 leading east out of the city were destroyed. Most of the coastal highways along the Gulf were impassable in places and most minor roads near the shore were still under water or covered in debris by August 30th.” Despite the torrential flooding and damaged roadways, “[i]t is estimated that in the days before Katrina, more than one million people evacuated from southeast Louisiana; given the few available routes and short advance warning time, this achievement was the most successful highway-based evacuation in U.S. history. One of the primary reasons for its effectiveness was Louisiana’s improved contraflow plan, which had been developed for this region only months previously […]" (Wolshon et al., 2006, p. 1). Being able to evacuate more people in less time than originally predicted was a tremendous life-saving feat, considering the enormity of Hurricane Katrina (See Appendix F for picture, NOAA, 2005). A review of New Orleans' contraflow plan reveals that "outbound traffic was nearly doubled—from 530 vehicles per hour/per lane (vphpl) to about 1,050 vphpl. […] When typical evacuation occupancies are considered, it would mean that an additional 15,000 to 20,000 potential lives were saved over a 12- to 15-hour evacuation just by using contraflow" (Wolshon et al., 2006, p. 4).

During Hurricane Rita, Texas "implemented a contraflow lane reversal on I-45, I-10, and on U.S. Highway 290. Traffic was not allowed to exit the designated routes except for food and gas, a feature of the evacuation plan that attempted to keep traffic and flow orderly throughout the evacuation. It's estimated that more than a million residents evacuated in advance of the storm" (Chiu, Zheng, Villalobos, Peacock, & Henk, 2008, p. 1). In contrast to Hurricane Katrina, as discussed above, New Orleans had a contraflow plan, yet failed to follow through with its implementation for Hurricane Rita, and consequently, stranded thousands of evacuees.

North Carolina captured the positive effects of contraflow during a simulated implementation on I-40 and the MLK intersection. Williams, Tagliaferri, Meinhold, Hummer, and Rouphail (2007) assess that "the significant capacity increase of this modification comes not only from additional lanes through the transition, but also from the ability to allow evacuation to essentially operate uninterrupted at the critical MLK

Parkway/College Road network node" (p. 66). Further review of this modified plan reveals impressive measurements (percentages relative to no contraflow):

Measurement	Original Plan	Revised Plan
Travel Time	153%	68%
Travel Delay	159%	13%
Delay per Mile	113%	9%
Average Speed	92%	209%

Figure 1. Improvement Results of Simulated Contraflow in North Carolina.

*Source(s):*Williams, B., Tagliaferri, A., Meinhold, S., Hummer, J., & Rouphail, N. (2007). Simulation and analysis of freeway lane reversal for coastal hurricane evacuation. *Journal of Urban Planning & Development*, *133*(1), 61-72. doi:10.1061/(ASCE)0733-9488(2007)133:1(61).

Despite being a simulated contraflow plan, having been applied to a crucial roadway for evacuations, the results reveal the real-world applicability of the plan and its presumed effectiveness.

Phased Evacuation

In terms of effectiveness, phased evacuations will also improve evacuations by spreading out or even limiting vehicle congestions. Wolshon et al. (2006) explains the importance of phased evacuations is to "call for evacuations in the most highly populated regions before traffic volume and congestion begin to build so they will not be trapped in the areas of greatest threat (p. 8). Phased evacuations will be initiated when a voluntary, recommended, or mandatory evacuation order has been issued. As each zone evacuates, they will be directed to enter, travel, and exit specific roadways to facilitate quick movement and limit congestion. During Hurricane Katrina, Louisiana's evacuation plan began with “a staged evacuation plan that identified the order of evacuation, starting with the lowest-lying areas first and a suggested timeline for initiation of contraflow. […] Additionally, the plan also discusses how major outbound arterials would be managed. Rather than minimize the likelihood of congestion on these routes, the final plan sought to avoid it as much as possible by prohibiting certain travel movements” (Wolshon et al., 2006, pp. 7-8).

In Cape Cod, MA, their Emergency Traffic Plan (ETP) was initiated after Hurricane Edouard in 1996. “Within hours of the Governor’s Declaration of a State of Emergency, a 6-8 hour backup, stretching an estimated 40 miles, occurred from the Sagamore Bridge to the Orleans Rotary along Route 6, due in large part to the challenges presented by the highway’s rotaries” (Massachusetts Emergency Management Agency, 2010). As a result of this massive backup, Cape Cod revised their ETP to focus on limiting causes of congestion. This was primarily “accomplished by prohibiting off-Cape access to Routes 6 and 28 at the base of both bridges, controlling access to certain exits for the ‘cross-Cape’ Scenic Highway and Sandwich Road, and creating flexibility in the opening and closing of exits by the MA State Police in order to expedite off-Cape traffic flow across the Sagamore and Bourne Bridges” (Cape Cod, 2010). Though this alternative is seldom discussed at length in current literature, this is a common practice prior to initiating contraflow, primarily due to its ability to reduce congestion (or capacity overload) and facilitate contraflow operations. As the above case studies show the effectiveness of contraflow and phased evacuation in decreasing congestion and evacuation time for populations ranging from a few hundred thousand to over a million, it is reasonable to presume that they will also be just as effective for Boston harbor, which contains a population of approximately 650,000 residents. It is recognized, however, considering the scope of this report is limited to case studies, additional research of Boston's transportation infrastructure will need to be conducted in order to adequately quantify the effectiveness of these strategies.

After reviewing the positive results of both contraflow and phased evacuations, the life- and time-saving benefits are evident; however, the utilization of contraflow as an alternative to traditional evacuation has not developed without noticeable obstacles. These obstacles involve issues relating to (a) planning and implementation, (b) accessibility, (c) safety, (d) cost, and (e) regional and interstate traffic.

Contraflow Limitation

From an engineering perspective, implementing contraflow will mean using roadways outside of their normal use; consequently, the normal "[s]igns, pavement markings, and safety features will not necessarily be visible to drivers traveling in the opposite direction. Reverse flow can also be confusing for drivers not familiar with this type of operation" (Wolshon, 2001, p. 108). In addition, Brian Wolshon, Assistant Professor in the Department of Civil and Environmental Engineering at the Louisiana State University, concludes that "[c]ontraflow operation, particularly one-way-out, virtually prohibits inbound access for any vehicles during the reversal. Before a hurricane, access for public safety personnel must be maintained to protect the health and safety of evacuees and their property. After the event, utility and construction crews need to be able to quickly access affected areas […]" (2001, p. 108). Having a good understanding of the access restrictions associated with contraflow will help evacuation planners choose an appropriate design and identify the extent of resources that will be required to implement and enforce contraflow.

Another aspect of implementation that should be considered is the ability of evacuees to exit contraflow lanes in order to access food, fuel, medical services, washrooms, and restroom facilities. For example, “The Georgia experience during Hurricane Floyd showed that numerous vehicles overheated or ran out of fuel while sitting in traffic gridlocks. For this reason the new Georgia DOT plans will now permit exits from all interchanges on its 95-mile contraflow segment out of Savannah” (p. 109).

The amount of resources needed to implement contraflow is considered to be a major drawback among emergency management professionals. Chui et al., (2008) explains “[c]ontraflow lanes take a vast amount of resources (hundreds of DOT or DPS staff) and time (6-10 hours) to set up and operate. Concerns [are] focused on whether the benefits warrant the utilization of resources that may be used in other areas of evacuation operations” (p. 1). Wolshon (2001) also points out that “once [contraflow] is in effect, state police, National Guard, and other law enforcement personnel will need to be stationed at all inbound entrance ramps to prevent unauthorized access into the contraflow lanes” (p. 109).

Due to the nature of contraflow, creating a potentially unfamiliar environment for drivers, safety is of utmost importance. The primary safety issue that arises from lane reversal is traffic accidents caused by opposing traffic. Wolshon (2001) affirms, “[O]ne of the most critical needs is the prevention of inbound vehicles from entering into the contraflow lanes. In most plans this will be accomplished using road closure barricades at all access points to the contraflow lanes" (p. 108).

When considering planning, implementation, and safety concerns, the issue of cost can become burdensome. Wolshon (2001) explains "[e]xcept for the cost of capital infrastructure improvements, the primary source of cost for contraflow evacuation is related to the personnel needs […]. For the 18 interchanges involved in North Carolina DOT [NCDOT] lane reversal, they will require 30 uniformed officers with cruisers to prohibit entry, […] 38 DOT field personnel to close the ramps, and 4 DOT personnel to assist with motorist information. The estimated total cost for construction items for the reversal of I-40 is $275,000" (p. 109).

In addition to the above considerations, regional and interstate movement from contraflow can lead to complicated political issues. For example, during Hurricane Katrina, the activation of contraflow would "involve collaboration among two states, eight parishes, and multiple law enforcement agencies, emergency planning offices, the local media, and volunteer organizations" (Kiefer, J., & Montjoy, R., 2006, p. 126, as cited in Ebbert, 2006). However, only months prior to Katrina, an agreement was forged between Mississippi and Louisiana, which prepared Mississippi to accommodate thousands of evacuees being contraflowed from Louisiana (Wolshon et al., 2006, p. 6). In the U.S. DOT's *Catastrophic Hurricane Evacuation Plan Evaluation: A Report to Congress* (2006), it is reported "most states have mutual-aid agreements and belong to the Emergency Management Assistance Compact (EMAC), a legal agreement among member States that outlines the procedures, including reimbursement and liability issues, for providing assistance to other member states in the event of an emergency or disaster" (p. ES-4). In addition to outlining standard procedures, the EMAC also facilitates the distribution of resources from other states. In the event of a large-scale evacuation, these resources may include fuel trucks, buses, portable Port-a-Potties, and debris removal equipment. However, this report also notes "exercises, traffic simulations, and other analyses to evaluate evacuation options for catastrophic incidents on the scale of Hurricane Katrina have not been conducted" (p. ES-4).

In consensus with the views discussed above, the National Review of Hurricane Plans and Policies reports "[h]ighway agencies agree that reverse flow operations will likely be inconvenient and confusing for drivers. They also expect contraflow to be labor intensive to initiate, difficult to enforce, and potentially dangerous for drivers" (Wolshon et al., 2001, p. 25). With an understanding of both the benefits and obstacles of contraflow, the final decision to apply these strategies to Boston's evacuation plan will lie with the Mayor of Boston and the Director of Emergency Management. When making the final decision, emergency management professionals will take into account environmental and behavioral characteristics that play a major part in evacuation strategy and implementation. Environmental characteristics include weather conditions associated with a hurricane; behavioral characteristics involve the time it takes to react to a hurricane and prepare for the subsequent evacuation.

Hurricanes drastically change the environment around them by introducing (1) coastal inundation due to storm surge, (2) widespread wind damage, and (3) widespread inland small stream and river flooding (NewEnglandClimatology, 2005). Due to the shape of Boston harbor, coastal inundation will not be a high risk; rather this area will be at risk of receiving both severe wind damage and inland flooding. In New England, specifically, "due to the rapid acceleration of most of [their] hurricanes, it is necessary that [appropriate] action be taken during a hurricane watch" (Tropical Definitions, 2005). A hurricane watch will be issued, if significant hurricane conditions exist, within 36 hours of its projected landfall. Significant rainfall will typically arrive 12-15 hours in advance of the storm (Tropical Cyclones, 2005). If Boston harbor were to experience a Category three hurricane, the highest expected to appear in the New England region, the National Hurricane Center (2010) estimates the following damage will occur: "There is a high risk of injury or death to people, livestock, and pets due to flying debris. […] Well-built frame homes can experience major damage involving the removal of roof decking and gable ends. […] Numerous windows will be blown out of high-rise buildings resulting in falling glass […]. Many trees will be snapped or uprooted, blocking numerous roads." All these environmental factors influence if, when, and how an evacuation will be implemented.

Behavioral characteristics, being directly linked to the surrounding environmental characteristics, effects physical response time in three phases: "(1) Mobilization time – the time required by evacuees to prepare for evacuation and enter the road network, (2) travel time – the time needed to travel along the road network, and (3) queuing delay time – the cumulative times for all stops caused by traffic congestion" (p. 3-17). These phases are known as clearance time. It is important to note "clearance time does not relate to the time any one vehicle spends traveling on the road network and does not include time needed for local officials to assemble and make a decision to evacuate" (p. 3-17). For example, “Georgia’s Emergency Operations Plan” (2010) has developed separate clearance times for the following variables: “Hurricane scenario, public response time, level of background traffic, and seasonal tourist occupancy” (p. 6). When considering variables for specific clearance times, the *Southern Massachusetts Hurricane Evacuation Study Technical Data Report* (1997) based their response on the following parameters: “(1) Evacuation population – population is assumed to be 20% greater, (2) evacuee response time – evacuees mobilize to evacuate in 2 hours instead of 4 hours, (3) shelter utilization – evacuees do not seek community shelters, but instead evacuate to other locations, and (4) traffic control measures – traffic control measures are implemented at the Bourne and Sagamore Bridge rotaries” (pp. 6-25-26). This report defines evacuation time as “the combination of roadway clearance time and dissemination time. Dissemination time includes time for officials to make evacuation decisions, mobilize support personnel, communicate between affected communities and the State, and disseminate evacuation directives to the public” (p. 9-4).

Developed in response to two major hurricanes that initiated large-scale evacuations and impacted at least four states, there is evidence that phased and contraflow evacuation strategies have helped in evacuating people out of coastal areas in a timely and safe manner. These life-saving strategies have been researched and documented by emergency management professionals and academics alike, with contraflow alone credited with increasing evacuation rates by upwards of 70%, and phased evacuation credited with being an effective threat-awareness tool used to evacuate the most vulnerable populations—classified as those residing close to the coast or a hurricane’s point of landfall—prior to these areas experiencing hurricane-force winds or storm surges. Throughout a decade of use in the field, the contraflow strategy in particular has had its benefits weighed against its obstacles. These obstacles involve issues relating to (a) planning and implementation, (b) accessibility, (c) safety, (d) cost, and (e) regional and interstate traffic.

Implementing contraflow involves hundreds of staff from up to a dozen or more agencies, and due to its nature of using roadways outside their normal purview, contraflow may become confusing for drivers and result in increased safety concerns. Safety concerns may also result from the inability to exit contraflowed areas for fuel, food, or restroom facilities. Considering the extent of resources required for implementation and the potential need to alter existing roadways, cost could become a burdensome issue. Additionally, interstate collaboration must be established prior to implementing contraflow; moving an entire population into another state requires a great deal of coordination in order to know how to effectively handle them without severely disrupting the daily economy of the accommodating state.

Ultimately, phased evacuation and contraflow strategies have the ability to help improve evacuations when they are properly applied and effectively coordinated. These strategies can be scaled and applied to either a small or very large geographic area. The ability to scale these strategies to fit nearly any geographic environment and any size budget shows promise in their ability to be (1) versatile, (2) cost-effective, and (3) highly beneficial tools.

Chapter III

Research Construction

Problem Statement

With the increase in population over the past 40 years, the need to develop effective evacuation plans has dramatically increased. Despite the steady increase in the number of people living in coastal areas, the number of roadways has remained the same. This presents a unique challenge for local emergency management directors who are responsible for developing and implementing plans to safely evacuate residents in times of disaster. As evidenced by Superstorm Sandy, hurricanes can and do affect the eastern coast; therefore, this tragic occurrence has validated the critical need to possess an effective evacuation plan. With the application of evacuation strategies, such as phased evacuation and contraflow, the task of moving people out of harms way has become a far less daunting challenge. This research project is directed to help Boston's emergency management directors and planners determine if phased evacuation and contraflow are suitable strategies for the evacuation of Boston's coastal population.

Hypotheses

My hypothesis, in conjunction with the literature review above, suggests a relationship between the use of phased evacuation and contraflow strategies and the effectiveness of motor vehicle evacuations. As previously discussed, states that have implemented these evacuation strategies have seen both a significant increase in the number of people evacuated, as well as a dramatic decrease in the amount of time required to move larger portions of the population as compared to states that have not implemented these strategies.

However, as these strategies have the potential of becoming confusing for both the planners and the residents being evacuated, implementation alone is not the only factor to be considered. The location of a state may require them to implement phased evacuation and contraflow on a more frequent basis, thus enabling them to continuously improve their technique. Also, as many southern states depend on the assistance of surrounding states to assist in evacuations, the task of incorporating these strategies becomes far less overwhelming due to the ability to borrow or build off of plans from partnering states. Consequently, as Boston is neither located in an area frequented by hurricanes on a regular basis, nor is Massachusetts surrounded by states that have practice in implementing phased evacuation or contraflow, these strategies may not provide any increase in the effectiveness or efficiency of motor vehicle evacuations.

Finally, the outcomes from this research may show these strategies fail to significantly improve the effectiveness or efficiency of motor vehicle evacuations. Outcomes of this research could direct Boston planners to research other strategies to help alleviate motor vehicle congestion during an evacuation.

Methodology

This research utilized the Real Time Evacuation Planning Model (RtePM), a computer modeling system, to analyze the application of phased evacuation and contraflow for an evacuation of Boston's coastal population, specifically South Boston and the Columbia Point peninsula of Dorchester. These coastal areas account for 27% of the total land area and 13% of the population for the entire Boston region. “RtePM is based on U.S. Census Bureau, U.S. Army Corps of Engineers, and proprietary road network data for all 50 states” (Old Dominion University, 2013, p. 1); therefore, data was collected from the results of individually run scenarios within the program. Each scenario was defined by setting various parameters within the program. These parameters will be discussed below.

Data Collection

The initial census and road network data required for this research was contained within RtePM. Programmers upload census and proprietary road network data from all 50 states in order to provide users with the ability to simulate evacuations by simply adjusting available parameters. Eliminating the need to input network data enables individuals who are not engineers to perform what is normally considered a complex, scientific evaluation. Since this data was pre-loaded, certain parameters were established to reflect the goal of this research. While there were four distinct scenarios, the following 10 parameters remained constant in each scenario: (1) 50% of the selected population evacuated, (2) 100% of the population utilized private vehicles, (3) 2.5 persons per vehicle, (4) 0% of pedestrians evacuated on foot, (5) 0% of the population utilized public transportation to evacuate, (6) evacuations took place within one day, (7) population numbers reflected daytime data, (8) traffic incidents occurred at a medium rate (e.g., an average of four accidents per evacuation scenario), (9) background traffic was rated as high, and (10) evacuations occurred over an period of 8 hours. Two of the four scenarios will contain two parts in order to analyze the application and non-application of phased evacuation (see Figure 2). In addition to these parameters, it should be noted that contraflow was only applied to I-90 West as this was the most feasible location for its application. While scenarios 1A and 2A contained only one evacuation zone, scenarios 1B and 2B split the area to be evacuated into two zones in order to simulate phased evacuation. Evacuation zone 1 consisted of South Boston and evacuated at the 2nd hour of the evacuation period. Evacuation zone 2 consisted of the Columbia Point peninsula of Dorchester and was the first zone to be evacuated. Additionally, to replicate a realistic response, 20 % of the population of downtown Boston evacuated as a shadow evacuation for each scenario. This type of evacuation occurs when a portion of the population outside the designated evacuation zone decides to evacuate without regard to their zone designation. The original developer of RtePM provided final verification of the scenarios.

Scenario	Contraflow	Phasing	Hour
1A	N	N	8
1B	N	Y	
2A	Y	N	
2B	Y	Y	

Figure 2. Scenario Parameters

Data Analysis

The variables in this study included 1) evacuation rate, 2) vehicles evacuated, 3) people evacuated, 4) evacuation end points, and 5) percentage evacuated. Each variable will be analyzed in increments of one hour. For purposes of this analysis, variables 1 through 5 were defined as the following:

1) Length of time it takes for the last vehicle to enter into the road network ("for example, 8 hours means that the last person begins their evacuation seven hours, 59 minutes and 59 seconds into the run of the simulation's evacuation period" (Old Dominion University, 2013, p. 19))

2) Total number of vehicles that have entered and exited the evacuation route.

3) Total number of people that have entered and exited the evacuation route.

4) Represents the "point of final destination or the point from which evacuees leave the scenario to continue traveling to their final destination" (Old Dominion University, 2013, p. 22).

5) Represents the percentage of people that have evacuated from the selected population.

A multivariate analysis of the final results from each scenario will be performed to evaluate (1) the routes chosen by evacuees and (2) the percentage of improvement in the total number of population evacuated.

Chapter IV

Results

Based on 2010 census data, RtePM calculated Boston's population at approximately 622,921. This study included a simulated evacuation of 50% of Boston's coastal population, along with a 20% shadow evacuation of downtown Boston. The population that evacuated from South Boston and Columbia Point was 39,393 from a total of 78,786 residents. Within downtown Boston, the zone designated for shadow evacuation, approximately 108,827 out of 544,473 residents, also evacuated. The evacuated population represents 23% of Boston's total population.

This simulation consisted of four scenarios: 1A, 1B, 2A, and 2B. Scenario 1A simulated a normal evacuation without the use of contraflow or phased evacuation, while 1B applied only phased evacuation. Scenario 2A applied contraflow without phased evacuation, while 2B applied both contraflow and phased evacuation. All minor and major arterial roads and highways within the evacuation zones were designated as evacuation routes. However, there were only six designated evacuation end points within each scenario: I-93 N, I-93 S, I-90 W, American Legion Hwy., Boylston Street, and Blue Hill Avenue. Interstate 93, which runs perpendicular to Boston, and I-90, which runs parallel to Boston, were selected because these are the only two roadways running in and out of the city. The remaining end points were selected because they serve as the primary corridors that accommodate high traffic volume and connect travelers to the major highways. Figure 3 illustrates the extent of the coastal evacuation zone, in addition to the shadow evacuation zone. The darker areas represent the coastal zone, while the lighter colored area to the left of the darker area represents the shadow evacuation zone.

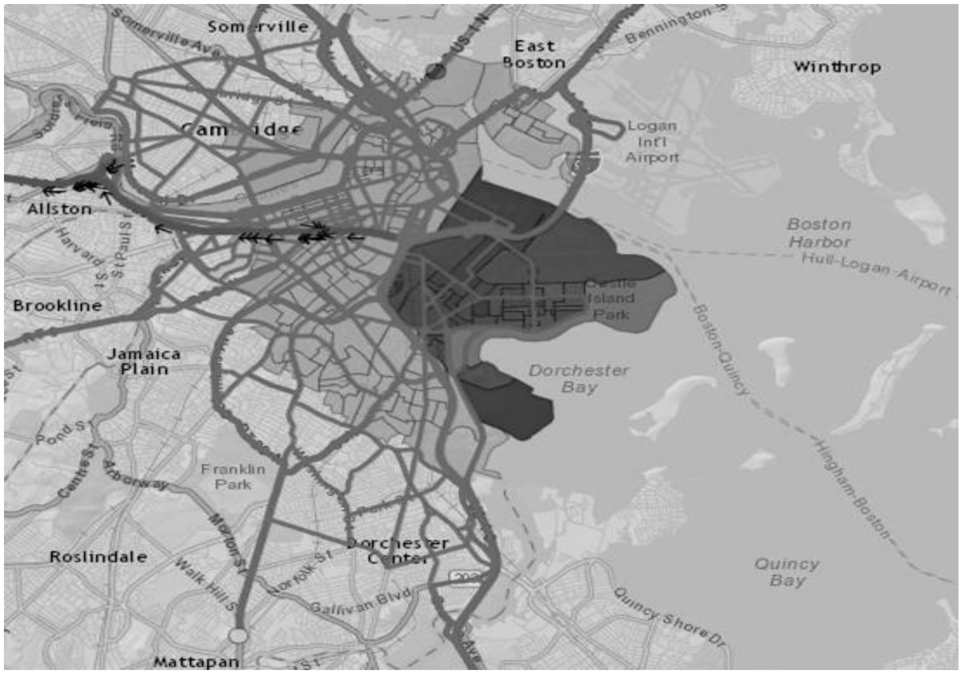

Figure 3. Boston Evacuation Zones

Routes Chosen by Evacuees

Simulations of scenarios 1A, 1B, 2A, and 2B showed that the application of contraflow and phased evacuation did not provide any noticeable increase in the number of vehicles evacuated. Instead of increasing the evacuation rate, the contraflowed route of I-90 West saw a decrease of nearly 1,000 vehicles when compared to results of an evacuation without contraflow. However, as this finding is contrary to known results, further verification of the simulation software will be needed before this finding can be accepted. Even so, if the evacuation rate remained the same with contraflow, it is possible the number of vehicles were not enough to overwhelm the normal capacity of I-90 West. Additionally, application of both contraflow and phased evacuation resulted in increased traffic volume on I-93 North and South. While fewer vehicles may have evacuated via the contraflowed routes on I-90 West, I-93 South saw an increase of over 6,000 vehicles when compared to a normal evacuation. Figures 4 and 5 illustrate the variations of vehicle disbursement between a normal and modified evacuation over an 8-hour period.

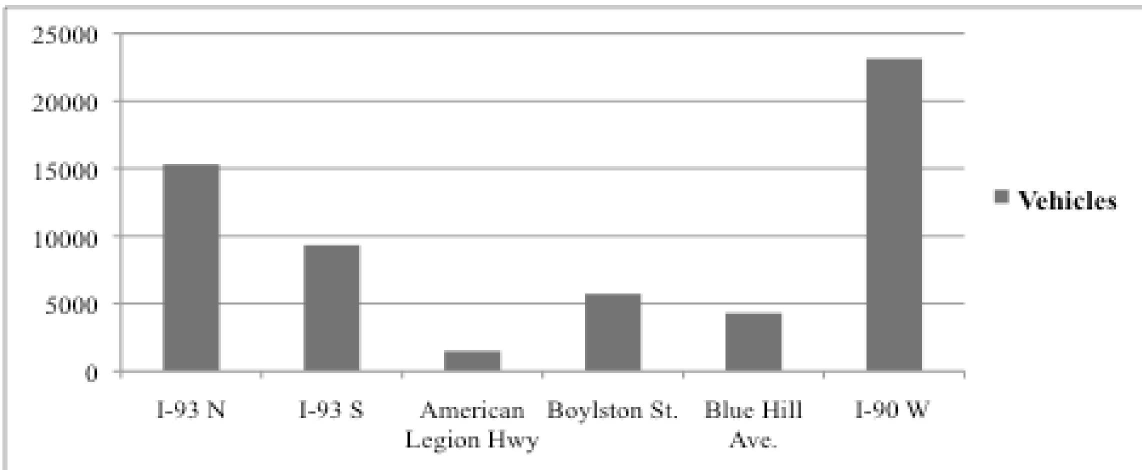

Figure 4. Vehicles Evacuated without Contraflow or Phased Evacuation

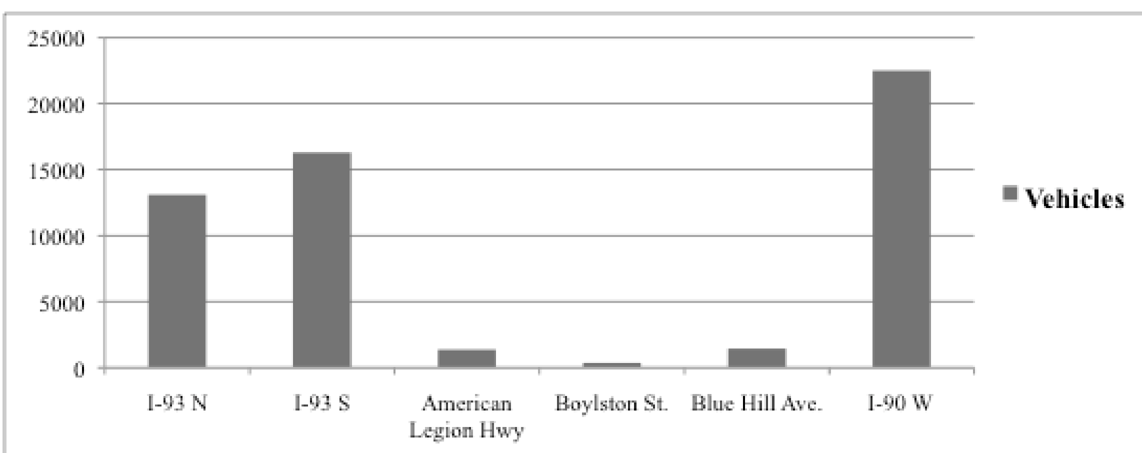

Figure 5. Vehicles Evacuated with Contraflow and Phased Evacuation

Furthermore, the application of contraflow and phased evacuation applied separately also did not result in an increase in the overall evacuation rate. While the results show contraflow caused traffic volume to decrease on I-90 W by over 3,000 vehicles and increase on Boylston Street and Blue Hill Avenue, further verification of simulation software is needed to ensure the accuracy of these results. Phased evacuation, on the other hand, did result in an increase of volume on I-90 West. However, later discussion will also reveal that this strategy in fact doubled the evacuation time. Figures 6 and 7 illustrate the comparison of these strategies over an 8-hour evacuation.

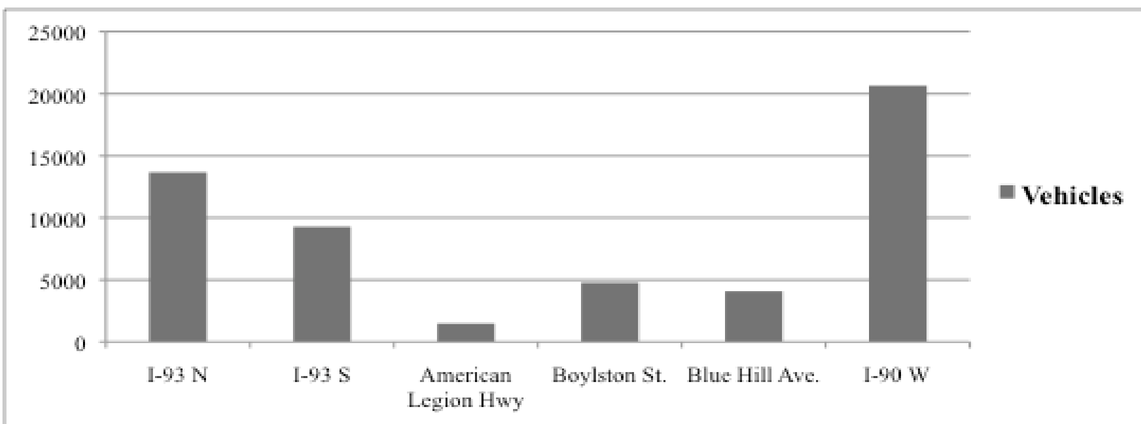

Figure 6. Vehicles Evacuated with Contraflow and No Phased Evacuation

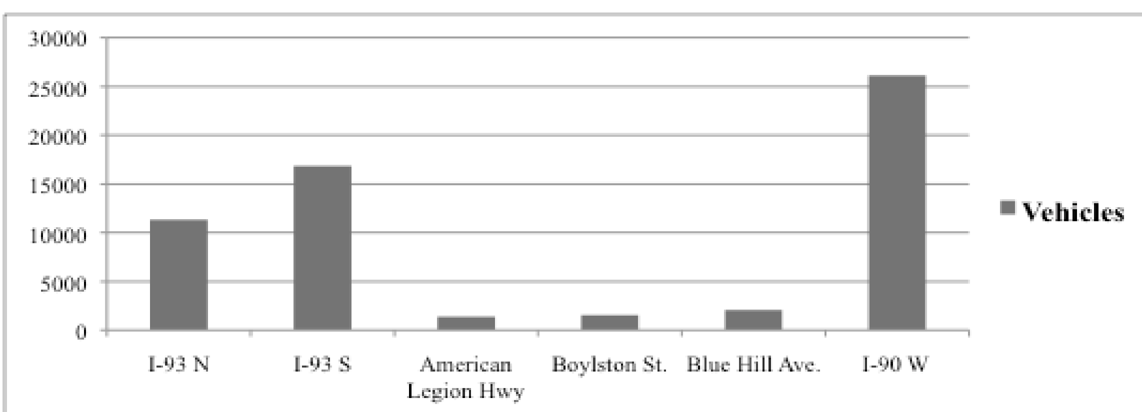

Figure 7. Vehicles Evacuated without Contraflow and with Phased Evacuation

__Improvement of Population Evacuated__

As the previous figures suggest, contraflow and phased evacuation did not increase the evacuation rate, or number of people evacuating, over the designated period of eight hours. At best, contraflow increased the rate of evacuation by a nominal 6% from hour 6 to 7, while the remaining 7 hours saw only a 1.5 to 2% increase. Moreover, as previously mentioned, phased evacuation prolonged the evacuation time from 8.2 hours to 16.2 hours. Figures 8 and 9 illustrate this significant variation in contraflow versus phased evacuation during what was originally an 8-hour evacuation.

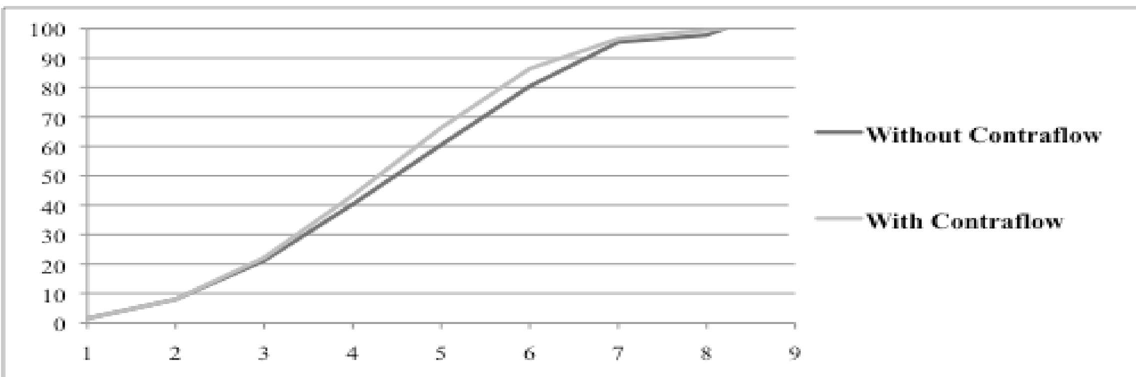

Figure 8. Percentage of Population Evacuated without Phased Evacuation

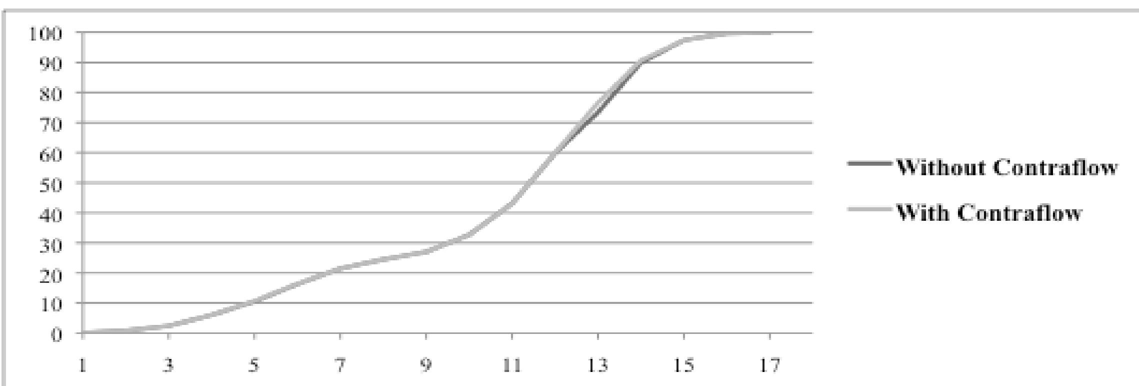

Figure 9. Percentage of Population Evacuated with Phased Evacuation

Research Limitations

Due to the use of a computer modeling system, the following five limitations to the applicability of this research are acknowledged. First, the network of roads and highways utilized by RtePM reflects network design as it existed as of December 2013; therefore, any construction or changes in road patterns will not be reflected in the results. Second, the population numbers reflect 2010 census data and will therefore not account for any potential increase or decrease in population size that may have occurred within the past four years. Third, evacuation routes selected by the user may not be a complete reflection of the routes residents would choose to take during an evacuation. Fourth, the evacuation end points—the location where evacuees exit the evacuation route—may not reflect the exact locations where evacuees choose to exit. Fifth, the research results may be skewed positively or negatively due to the fact they were produced from a computer program. Despite verification of each scenario, the negative contraflow results suggest the possibility an error exists within the simulation program. Additional discussion and examination of verification procedures should be addressed in future research.

Chapter V

Conclusion

This research concludes that when an evacuation anticipates moving 60,000 vehicles or less from coastal areas, contraflow may not be necessary, while phased evacuation will require thorough planning prior to implementation to avoid extending an evacuation beyond the scheduled timeframe.

Not withstanding the RtePM's verification concerns, Boston planners may take the results of contraflow to suggest that this strategy may not improve evacuations when they involve 60,000 vehicles or less because the normal capacity of I-90 West is capable of accommodating this level of demand. However, despite Boston's infrequent exposure of natural and man-made disasters, there may come a time when 100% of the population is required to evacuate. Contraflow may be more effective in this situation due to more demand and more opportunities to relieve potential congestion. As the total evacuation of Boston was beyond the scope of this research, further study is necessary to fully analyze this scenario.

Additionally, the results of phased evacuation may aid Boston planners in deciding when to issue an evacuation order. With the possibility that a regular 8-hour evacuation might turn into a 16-hour evacuation, planners will need to assess the timing and planning of a large-scale evacuation in order to ensure the most vulnerable populations are removed well before hurricane force winds make landfall. Planning assessments are critical when dealing with densely populated areas, such South Boston and Columbia Point, which have limited roadways, and therefore have limited capacity to move people out. This research illustrates the critical nature of planning. Columbia Point was designated as evacuation zone one due to its inherent vulnerability to an approaching hurricane. As a result, they were required to evacuate through South Boston, designated as zone two. With only a two hour head start, it is likely the roadways were still congested with zone one evacuees by the time zone two began evacuating.   Thus, knowing the length of time required to fully evacuate the vulnerable population is critical to the timing of issuing an evacuation order.

However, these findings must be weighed against the following ten parameters that defined the boundaries of this research: (1) 50% of the selected population evacuated, (2) 100% of the population utilized private vehicles, (3) 2.5 persons per vehicle, (4) 0% of pedestrians evacuated on foot, (5) 0% of the population utilized public transportation to evacuate, (6) evacuations took place within one day, (7) population numbers reflected daytime data, (8) traffic incidents occurred at a medium rate (e.g., an average of four accidents per evacuation scenario), (9) background traffic was rated as high, and (10) evacuations occurred over an period of 8 hours. Therefore, scenarios involving public transportation; pedestrian evacuation; and evacuations occurring during evenings, weekends, or holidays are outside the scope of these findings.

Further research can be conducted to better understand the application and evaluation of these scenarios with Boston's current evacuation procedures. Additional research may also be conducted to evaluate how these strategies influence scenarios that were outside the scope of this research.

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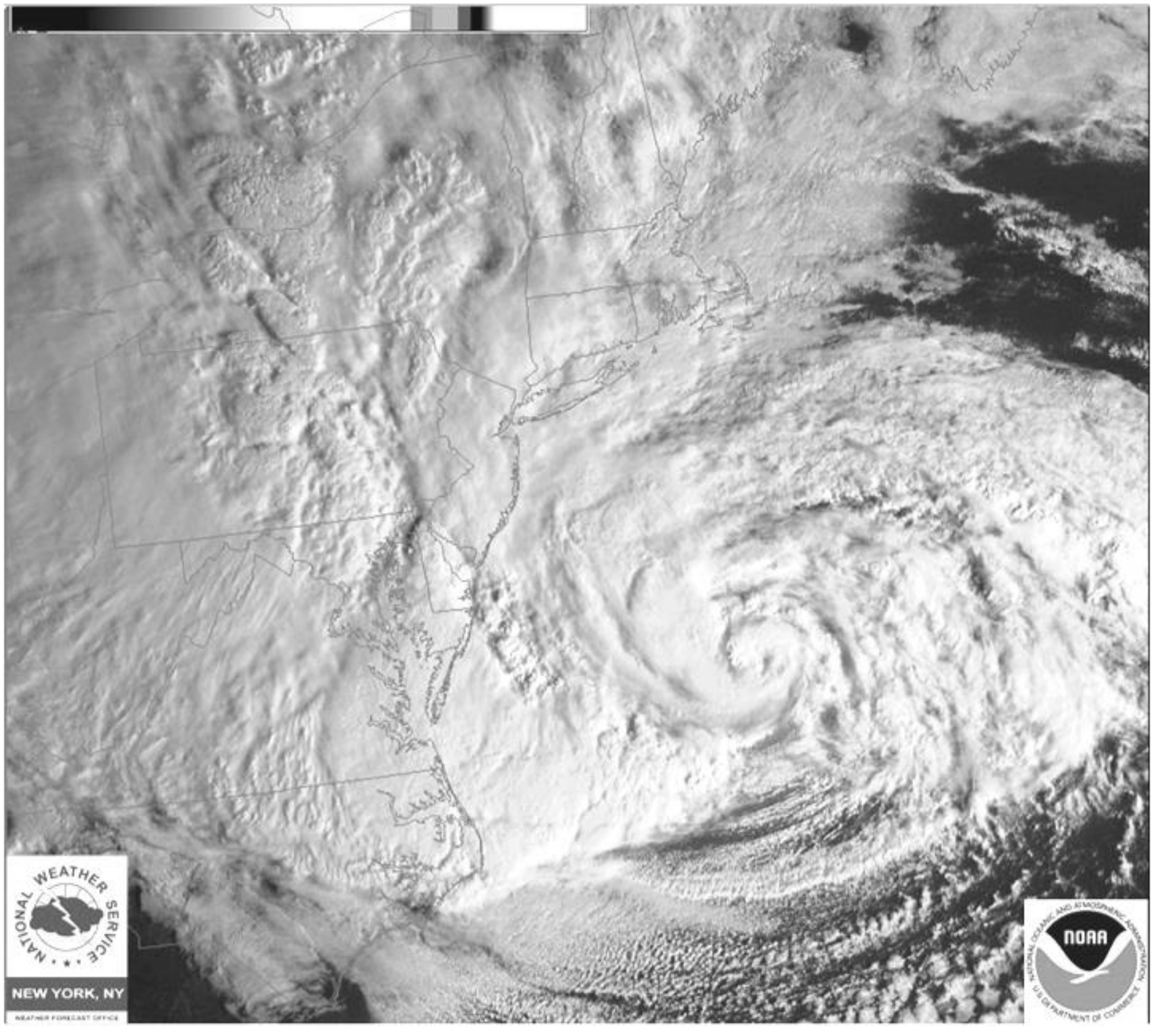
APPENDIXES

APPENDIX A:

Superstorm Sandy - 2012


NATIONAL WEATHER SERVICE
NEW YORK, NY
NOAA

APPENDIX B:

Contraflow Designs

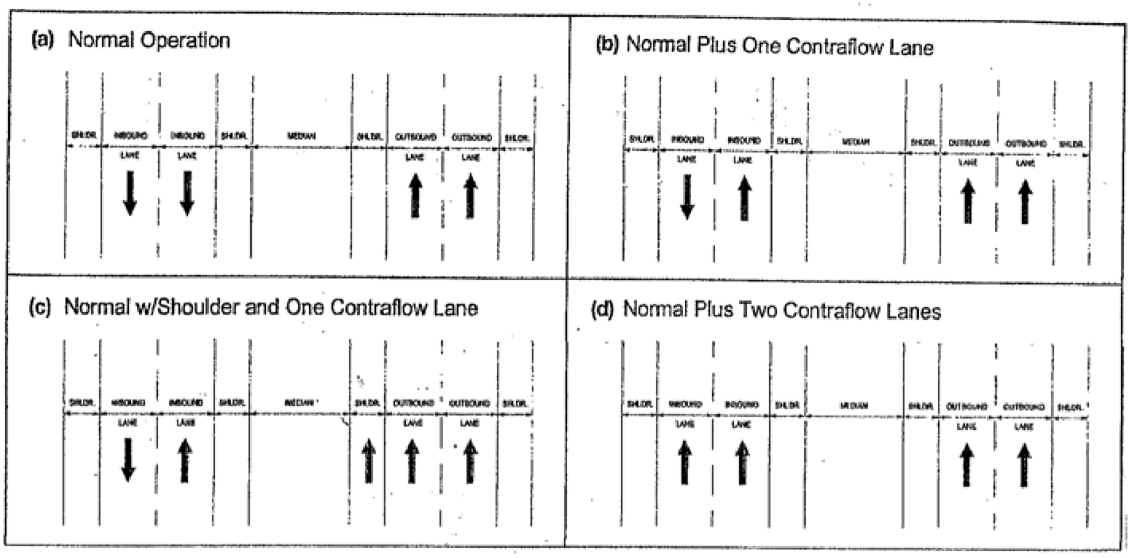


FIG. 1. Freeway Contraflow Lane Use Configurations for Evacuations

APPENDIX C:

Applied Contraflow

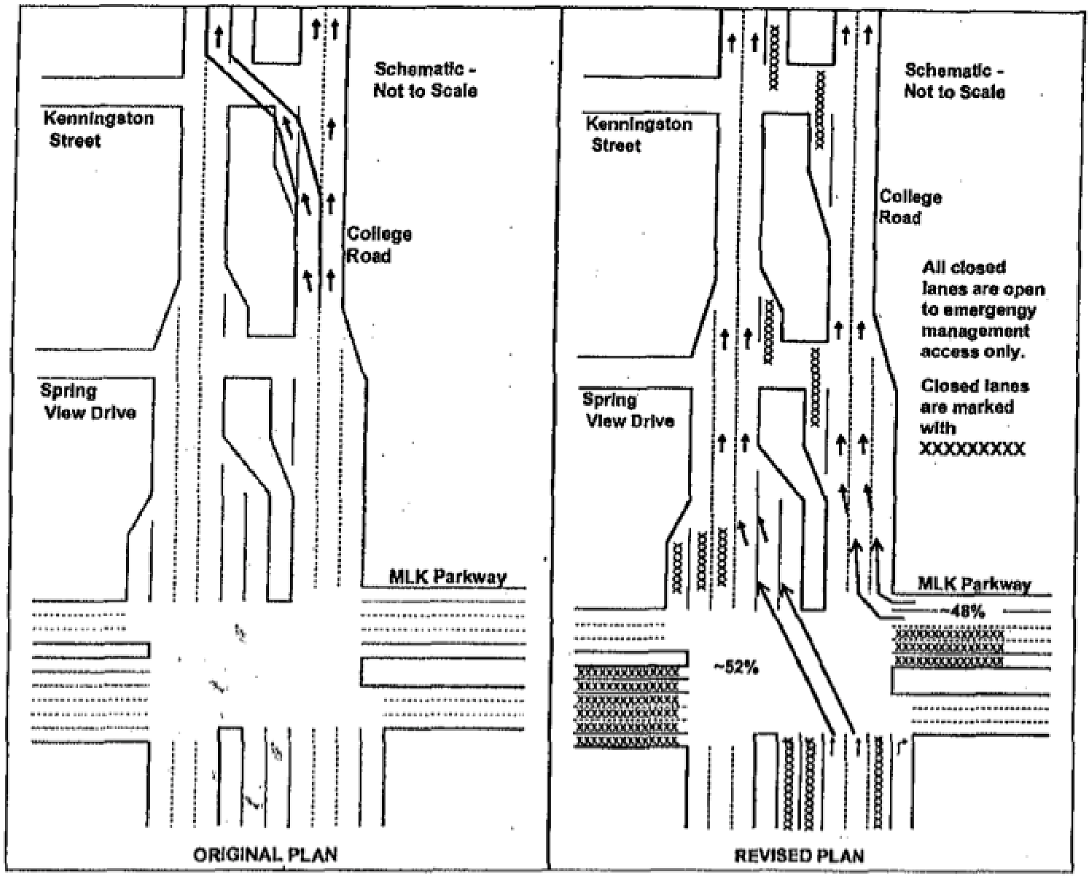


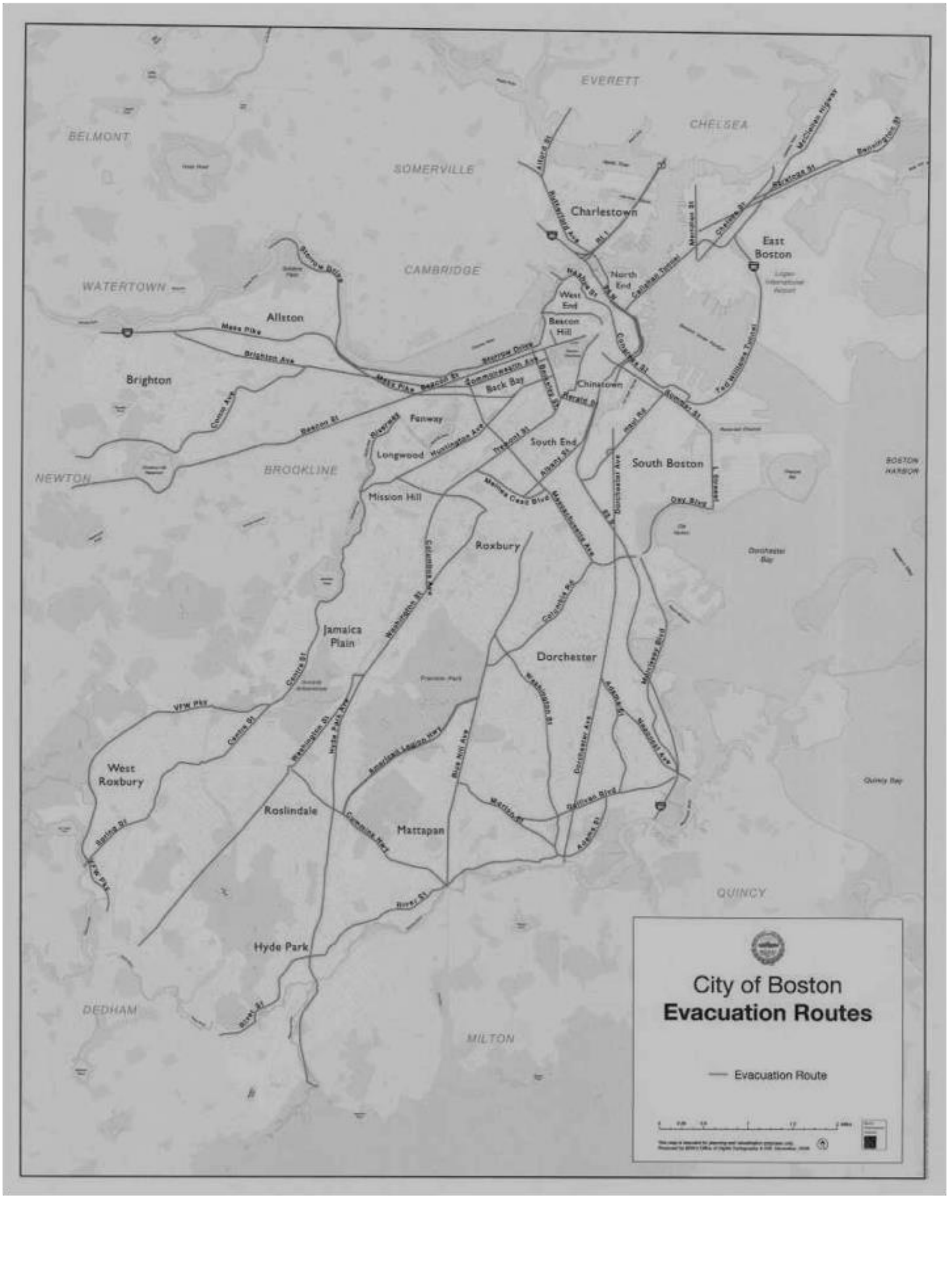
Fig. 4. Comparison of original and revised plans of transition to contraflow

Table 1. Maximum Queue from the Lane Drop (Miles)

	Percent relative to no contraflow	
Measure of effectiveness	Original contraflow plan (%)	Revised (MLK) contraflow plan (%)
Total vehicle hours travel time	153	68
Vehicle hours of delay	159	13
Minutes of delay per mile	113	9
Average speed	92	209

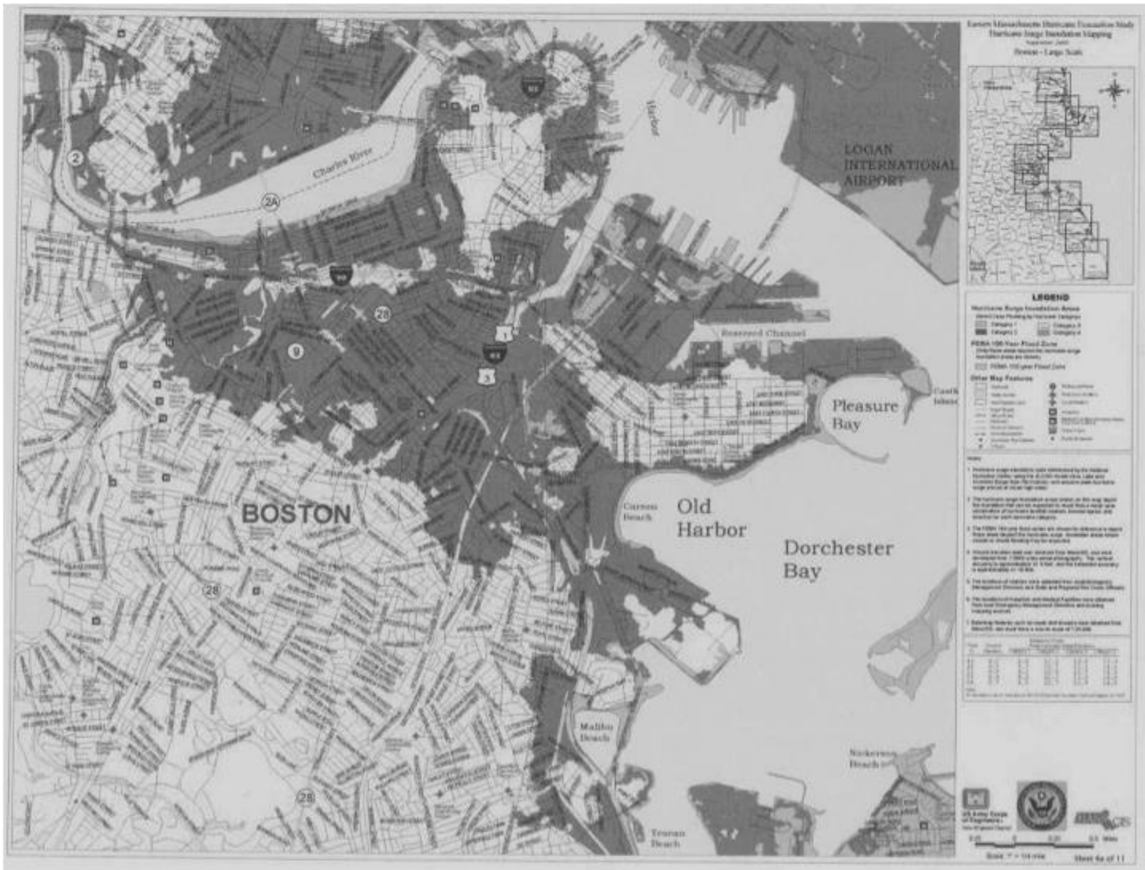
APPENDIX D:

Boston Evacuation Routes


City of Boston
Evacuation Routes
Evacuation Route
EVERETT
CHELSEA
BELMONT
SOMERVILLE
Charlestown
East Boston
CAMBRIDGE
WATERTOWN
Allston
North End
West End
Beacon Hill
Brighton
Back Bay
Chinatown
Fenway
South End
Longwood
South Boston
NEWTON
BROOKLINE
Mission Hill
Roxbury
Jamaica Plain
Dorchester
West Roxbury
Roslindale
Mattapan
QUINCY
Hyde Park
DEDHAM
MILTON

APPENDIX E:

Boston Inundation Map


LOGAN
INTERNATIONAL
AIRPORT
Charles River
Reserved Channel
Pleasure
Bay
BOSTON
Old
Harbor
Dorchester
Bay
Carson
Beach
Malibu
Beach
Nickerson
Beach
Tenean
Beach
LEGEND