



**NAVAL
POSTGRADUATE
SCHOOL**

MONTEREY, CALIFORNIA

THESIS

**REDUCING THE “GAP OF PAIN”: A STRATEGY FOR
OPTIMIZING FEDERAL RESOURCE AVAILABILITY
IN RESPONSE TO MAJOR INCIDENTS**

by

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March 2007

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REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response including the time for reviewing instruction, 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 (Leave blank)	2. REPORT DATE March 2007	3. REPORT TYPE AND DATES COVERED Master's Thesis		
4. TITLE AND SUBTITLE: Reducing the "Gap of Pain": A Strategy for Optimizing Federal Resource Availability in Response to Major Incidents			5. FUNDING NUMBERS	
6. AUTHOR Curtis L. Heidtke				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			10. SPONSORING / MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited			12b. DISTRIBUTION CODE A	
13. ABSTRACT (maximum 200 words) In large-scale domestic disasters, a temporal gap frequently develops between the exhaustion of state and local resources and the arrival of federal resources. To date, strategies for reducing this so-called "gap of pain" have not been based upon scientific methodology. This thesis reviews four alternatives for ensuring continuous availability of critical commodities: pre-positioning, pre-emptive federal action, time-phased deployment, and surge transportation. For a given scenario, the optimum approach is likely to be some combination of these alternatives. Stochastic modeling using optimization techniques holds great promise for producing efficient and effective strategic solutions. This thesis evaluates one such model using two notional scenarios affecting the Washington, D.C. metropolitan area: a Category 4 hurricane and a one-kiloton nuclear explosion near the city center. The results reinforce the validity of using this method to generate viable strategic alternatives for consideration by senior decision-makers. With additional development and testing, the model may be productively applied to a range of natural and man-made incidents, in disparate locations.				
14. SUBJECT TERMS Disaster Relief; Humanitarian Logistics; Stochastic Models; Pre-Positioning; Surge Transportation; Pre-Deployment			15. NUMBER OF PAGES 105	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UL	

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IN RESPONSE TO MAJOR INCIDENTS**

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Submitted in partial fulfillment of the
requirements for the degree of

**MASTER OF ARTS IN SECURITY STUDIES
(HOMELAND SECURITY AND DEFENSE)**

from the

**NAVAL POSTGRADUATE SCHOOL
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ABSTRACT

In large-scale domestic disasters, a temporal gap frequently develops between the exhaustion of state and local resources and the arrival of federal resources. To date, strategies for reducing this so-called “gap of pain” have not been based upon scientific methodology. This thesis reviews four alternatives for ensuring continuous availability of critical commodities: pre-positioning, pre-emptive federal action, time-phased deployment, and surge transportation. For a given scenario, the optimum approach is likely to be some combination of these alternatives. Stochastic modeling using optimization techniques holds great promise for producing efficient and effective strategic solutions. This thesis evaluates one such model using two notional scenarios affecting the Washington, D.C. metropolitan area: a Category 4 hurricane and a one-kiloton nuclear explosion near the city center. The results reinforce the validity of using this method to generate viable strategic alternatives for consideration by senior decision-makers. With additional development and testing, the model may be productively applied to a range of natural and man-made incidents, in disparate locations.

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LIST OF ACRONYMS

A300	Airbus A300 commercial aircraft
AA	Affected Area
ACMI	Aircraft, cargo, maintenance and insurance; a type of aircraft lease
AFB	Air Force Base
ANGS	Air National Guard Station
B747	Boeing 747 commercial aircraft
BH	Block Hours
C-17	Boeing C-17 Globemaster III military cargo aircraft
C-130J	Lockheed Martin C-130J Hercules military cargo aircraft
CH-53G, CH-53S	CH-53 Sea Stallion military helicopter, configured for “general” and “special” missions, respectively
CRAF	Civil Reserve Air Fleet
DC-10	McDonnell-Douglas (now Boeing) DC-10 commercial aircraft
DCO	Defense Coordinating Officer
DHS	U.S. Department of Homeland Security
DOD	U.S. Department of Defense
DOT	U.S. Department of Transportation
DTRA	Defense Threat Reduction Agency
EMAC	Emergency Management Assistance Compact
EPR	Emergency Preparedness and Response
ESF	Emergency Support Function
ETC	Emergency Transportation Center
FCO	Federal Coordinating Officer
FEMA	Federal Emergency Management Agency
HSPD	Homeland Security Presidential Directive
HMMWV	High-Mobility Multipurpose Wheeled Vehicle
ICS	Integrated Command System
JFO	Joint Field Office
JIT	Just-in-Time
JRSOI	Joint Reception, Staging, Onward Movement and Integration
JTF	Joint Task Force

MCC	Movement Coordination Center
MD-11	McDonnell-Douglas (now Boeing) MD-11 commercial aircraft
MRE	Meals Ready to Eat
MV-22G, MV-22S	Bell/Boeing MV-22 Osprey tilt-rotor military aircraft, configured for “general” and “special” missions, respectively
NIMS	National Incident Management System
NRCC	National Response Coordination Center
NRP	National Response Plan
NRP-CIA	National Response Plan—Catastrophic Incident Annex
POM	Pre-positioning Optimization Model
PS	Potential Survivor
RC	Replacement Cost
RL	Relief Location
RRCC	Regional Response Coordination Center
TM	Transportation Means
TX-TF1	Texas Task Force 1; a US&R team
UPS	United Parcel Service, Inc.; a major commercial cargo carrier
US&R	Urban Search and Rescue; refers to 28 specialized civilian search and rescue task forces organized and equipped under FEMA to respond anywhere in the U.S. to an emergency or disaster
VISA	Voluntary Intermodal Sealift Agreement
VSTOL	Vertical/Short Takeoff and Landing
WMD	Weapon of Mass Destruction
“General” mission	Transportation of commodities and relief workers
“Special” mission	Transportation of rescued survivors

ACKNOWLEDGMENTS

I would like to thank my two thesis advisors, Professor Javier Salmeron and Professor Aruna Apte, for their unwavering faith in me and my work, their wise counsel, and their insistence on academic excellence. This thesis is immeasurably better as a result. In particular, I would like to thank Professor Salmeron for patiently explaining the concepts involved in the Pre-positioning Optimization Model (POM) to this plodding student, many years removed from academic study of the scientific disciplines involved. I would also like to thank Professor Ted Lewis for his encouragement and guidance, especially in narrowing the scope of the thesis and in providing a knowledge bridge between the very different worlds of homeland security and operations research.

Many people helped me in my journey toward understanding. These include Mr. Kenneth Wright of Texas Task Force 1 Urban Search & Rescue Team; Mr. Matt Trachtman of Transgroup Worldwide Logistics; Major Ben Cacioppo of the Defense Threat Reduction Agency; Captain Ricardo Castro of the Seattle Fire Department's Haz-Decon Team; Mr. Chris Voss of the District of Columbia Emergency Management Agency; Mr. Robert Beesley, P.E., Director of Development for the Memphis-Shelby County Airport Authority; Mr. Guy Cobb of Federal Express; and Mr. Mark Stidd of the Joint Force Headquarters—National Capital Region.

I owe a particular debt of gratitude to my supervisor, COL (USA) William Barto, and his predecessor, COL (USA) Sarah Green, for encouraging me throughout this masters program and in particular through the demanding thesis preparation period.

I would like to specially acknowledge and thank the creator (with Professor Salmeron) of the POM, Singapore Air Force Captain Ee Shen Tean. His dedication to his research, and the greater good it may someday effect in the field of humanitarian logistics, inspired and motivated me to continue my own efforts.

Finally, to my wife Susan and my children, your love and support kept me going. We made it, together.

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I. INTRODUCTION

Throughout human history, governments have been expected to provide for the safety and security of their citizenry. Necessarily, this included responding to an array of disasters, both natural and man-made. To a great degree, the success or failure of past relief efforts has turned on the speed and efficiency with which the government delivered critical commodities to affected individuals. In the United States, the federal government's logistics processes for responding to emergencies and disasters have been largely *ad hoc*. That approach has been a failure, as dramatically illustrated by the Hurricane Katrina response. As Department of Homeland Security (DHS) Secretary Michael Chertoff admitted, "FEMA's logistics systems [in Katrina] were not up to the task."¹ In its report on the Katrina response, the Senate Committee on Homeland Security and Governmental Affairs was more blunt: "FEMA's logistics system failed out of the box[.]"²

The direct consequence of this failure was an increase in human suffering among the victims of the hurricane. The inadequacy of the federal logistics system was manifested in a temporal gap that developed between the exhaustion of state and local resources and the excruciatingly slow development of an effective federal re-supply effort. This resource gap has been colloquially referred to as the "gap of pain."³

This gap of pain is not inevitable. This paper hypothesizes that the gap can be reduced or eliminated by the strategic application of mathematical optimization models like the ones which have proven extremely successful in commercial and military supply

¹ "DHS Vows to Reform Disaster Response," *National Defense* 90 (April 2006), 9.; Committee on Homeland Security and Governmental Affairs, *Hurricane Katrina: A Nation Still Unprepared*, 109th Cong., 2nd sess., 2006, 375.

² Senate Committee on Homeland Security and Governmental Affairs, *Hurricane Katrina: A Nation Still Unprepared*, 109th Cong., 2nd sess., 2006, S. Rep. 109-322, 598.

³ The term "gap of pain" was borrowed from a PowerPoint briefing given by Army Brigadier General Anthony Cuculo on the lessons learned from Hurricane Katrina. Brig Gen Cuculo is the Commander of the Joint Center for Operational Analysis and Lessons Learned (JCOA), a subordinate organization of U.S. Joint Forces Command. Joint Center for Operational Analysis, *National Response to Catastrophic Events: Applied Lessons for Consequence Management*, PowerPoint briefing, Colorado Springs, Colorado: 9 January 2006 (hereinafter the "JCOA Report").

chain management. One such model, the Pre-positioning Optimization Model (POM), is employed to validate the hypothesis and demonstrate the applicability of the concept.

There is no questioning the importance of the logistics function to the overall relief effort. From before the creation of the National Incident Management System (NIMS), the Incident Command System (ICS) included Logistics as one of its five major functional areas.⁴ Lynn Fritz, an expert on humanitarian logistics and founder of the nonprofit Fritz Institute, has estimated that disaster relief is 80 percent logistics.⁵ Anisya Thomas, the Fritz Institute's managing director, adds that logistics "can be the difference in people making it or not making it."⁶ Yet, despite unequivocal evidence of the significance of supply chain management to effective disaster relief, there has been little research on the humanitarian relief supply process.⁷ Only a handful of humanitarian relief organizations have prioritized the creation of high-performing logistics and supply chain operations.⁸ Sadly, national governments, including the U.S. federal government, are even farther behind. There are a number of reasons that might help explain the lack of progress. At various times and to various degrees, legal, fiscal, organizational, political, and technological considerations have created impediments. Regardless of the precise cause, the reality is that, in the words of the bilateral House Committee that investigated the Katrina response, the federal logistics system for supplying aid to disaster victims is "broken and needs to be fixed."⁹

⁴ U.S. Department of Homeland Security, *National Incident Management System* (Washington, D.C.: U.S. Department of Homeland Security, 2004).

⁵ Joseph Bonney, "Life-and-Death Logistics," *The Journal of Commerce* 6, no. 2 (January 10, 2005), 6.

⁶ Ibid.

⁷ Benita M. Beamon, "Humanitarian Relief Chains: Issues and Challenges" (paper presented at the 34th International Conference on Computers and Industrial Engineering, San Francisco, CA, November 14-16, 2004).

⁸ Anisya S. Thomas, "Humanitarian Logistics: Matching Recognition with Responsibility," *Asia Development Review*, June 2005, 29, http://www.fritzinstitute.org/PDFs/InTheNews/2005/ADR_0605.pdf (accessed October 2006).

⁹ U.S. Congress, House of Representatives Select Bipartisan Committee to Investigate the Preparation for and Response to Hurricane Katrina, *A Failure of Initiative: Final Report of the Select Bipartisan Committee to Investigate the Preparation for and Response to Hurricane Katrina*, 109th Cong., 2nd sess. (Washington, D.C.: GPO, 2006) (hereinafter the "House Report on Katrina").

Incredibly, examples of federal logistics mismanagement in disaster responses extend back decades. In a 1953 after-action report on U.S. military assistance in the aftermath of severe floods in the Netherlands, the U.S. Army Europe Headquarters historian noted some of the same problems with lack of pre-planning and inadequate supplies that plagued Hurricane Katrina responders over 50 years later.¹⁰ In 1989 Hurricane Hugo smashed into Charleston, South Carolina, leaving thousands homeless in a disaster zone spanning hundreds of square miles. After it passed, it took the Federal Emergency Management Agency (FEMA) ten days to open the first disaster claim processing center in the city, prompting then-U.S. Senator Ernest “Fritz” Hollings to call the agency “the sorriest bunch of bureaucratic jackasses I’ve ever worked with.”¹¹ In 1993 Hurricane Andrew destroyed vast swaths of southern Florida. A subsequent Government Accountability Office (GAO) report faulted FEMA for its slow delivery of vital services for the hurricane’s victims.¹² In post-disaster Senate subcommittee hearings, then-U.S. Senator Bob Graham of Florida opined that “FEMA did poorly,” because it “was asked to do a job which was beyond its capability.” Sen. Graham introduced legislation that would have granted the President authority to direct the U.S. military to take the lead in “megadisasters.”¹³ Again in 1999, a major hurricane moved up the U.S. east coast. This time, Hurricane Floyd dumped up to 20 inches of rain over eastern North Carolina, leaving victims clinging to trees and waiting on their roofs for rescue as floodwaters rose at a rate of a foot an hour. Along with two other teams, members from Pennsylvania Urban Search and Rescue (US&R) Task Force One (PA-TF1) were pre-deployed to the area in advance of the storm. In a moving report of their experiences, the team’s frustration at the lack of rescue boats and equipment is palpable. Team member Tim Sevison exclaims, “We can’t get FEMA to understand that

¹⁰ Headquarters U.S. Army Europe, Historical Division, *U.S. Military Flood Relief Operations in the Netherlands* (Karlsruhe, Germany: U.S. Army, 1953).

¹¹ Bruce Smith, “Katrina Complaints Echo those of Hugo Response,” *Mobile Register*, sec. B, September 7, 2005.

¹² *House Report on Katrina*, 136.

¹³ Senate Committee on Environment and Public Works, *Committee on Environment and Public Works, Lessons Learned from Hurricane Andrew: Hearing before the Subcommittee on Toxic Substances, Research and Development of the Committee on Environment and Public Works*, 103rd Cong., 1st sess., 1993, S. Hrg. 103-86, 2, <http://digital.library.miami.edu/gov/Andrew.html> (accessed 22 February 2007).

it would be a good idea to add swiftwater/flood rescue components to all of the US&R Task Forces.” Lt. Douglas Bair, a PA-TF1 rescue squad officer, said poignantly, “I wish I could grab some politicians and shake them into allowing this to happen before another 100 people die because nobody is available to rescue them.”¹⁴

The slowness and inadequacy of the federal response, expressed in the frustrations of responders, state and local officials, and victims, are common threads throughout all of these disasters. Six years after Hurricane Floyd, these same themes repeated themselves in the response to Hurricane Katrina. In its findings, the House Report on Katrina blandly noted that “[a]n overwhelmed logistics system made it challenging to get supplies, equipment, and personnel where and when needed.”¹⁵ Those who lived through the catastrophe were much less circumspect. The mayor of East Baton Rouge Parish described the logistics response as “management by crisis.”¹⁶ It took almost four days after Katrina made landfall before basic necessities began to arrive for the survivors.¹⁷ When they did, there was not enough. The Mississippi Emergency Management Agency (MEMA) reported receiving less than 15 percent of its requested quantities of water, ice, and Meals Ready to Eat (MREs). As a consequence, MEMA was forced to ask for help from other states, and to purchase the remainder of the needed supplies on the commercial market. When the Alabama Emergency Management Agency requested 100 trucks of water and 100 trucks of ice, FEMA sent 17 trucks of water and 16 trucks of ice.¹⁸ In Congressional hearings afterward, former FEMA director Mike Brown acknowledged that “FEMA has a logistics problem.” He blamed the lack of a supply tracking system, stating if “[y]ou don’t have a unified command, [you] kind of go into an *ad hoc* mode.”¹⁹

¹⁴ Nancy J. Rigg, “Pennsylvania to the Rescue: PA-TF1 on Scene during Hurricane Floyd,” CFS Press, Asheville, NC, <http://www.cfspress.com/riggfloyd.htm> (accessed 21 February 2006).

¹⁵ *House Report on Katrina*, 5.

¹⁶ *Ibid.*

¹⁷ Bud La Londe, “Fiddling while Rome Burns?” *Supply Chain Management Review* 9, no. 7 (October 2005), 6.

¹⁸ *House Report on Katrina*, 321.

¹⁹ *Ibid.*

Mr. Brown and FEMA should not have been surprised that the logistics system performed so poorly. In a March 2005 report, a government consultant concluded that FEMA needed an improved logistics capability and asset visibility.²⁰ FEMA's own post-Katrina report warned: "For years FEMA has approached disasters almost timidly. FEMA should be attacking with sledgehammers, not fly swatters. Specific changes in logistics need immediate attention."²¹ The Federal Coordinating Officer (FCO) in Louisiana told investigators from the Senate committee examining the federal government's Katrina response that FEMA's failure to track supplies "has been a problem at every disaster I'm aware of."²²

The inescapable conclusion is that the federal government's humanitarian logistics system is dysfunctional, and has been for some time. As current FEMA Director R. David Paulison said in comparing the post-Hurricane Andrew recommendations with those made after Katrina, over a decade later, "You could have taken 'Andrew' out and put 'Katrina' in."²³ According to University of Pennsylvania political science professor Donald Kettl, some of the delay in implementing change may be attributed to fiscal constraints and bureaucratic inertia. Says Kettl:

The big crises like Sept. 11 and Katrina challenge us and punish us for failing to adapt. But these [post-Katrina] reports call for really dramatic, radical changes in ways that disrupt the patterns of political power and standard operating procedure. So it's a lot easier to let the day-to-day pressures rule instead of confronting the issues that we know we have to deal with.²⁴

²⁰ Lara Jakes Jordan, "Latest Review of FEMA Echoes Pre-Katrina Advice," *Seattle Post-Intelligencer*, Nation/World, April 4, 2006, http://seattlepi.nwsourc.com/national/265347_katrina05.html (accessed 22 February 2007).

²¹ Ibid.

²² Committee on Homeland Security and Governmental Affairs, *Hurricane Katrina: A Nation Still Unprepared*, 375.

²³ Jordan, *Latest Review of FEMA Echoes Pre-Katrina Advice*.

²⁴ Ibid.

This institutional heel-dragging exacts a human toll. From one disaster to the next, each failure of the federal humanitarian logistics system translates into increased human suffering. As the Senate investigative committee concluded, “Ordinary people forced to endure inhuman circumstances were the victims of these failures.”²⁵

A. DEFINING THE ISSUE

After nearly every major domestic disaster, questions are raised about the efficacy of the incremental process by which federal aid is brought to bear. The traditional paradigm of waiting until local and state resources are overwhelmed has long roots, dating back at least as far as the Federal Response Plan (FRP). In testimony to a Senate subcommittee after Hurricane Andrew, a FEMA official opined that “the guiding principle of disaster relief has always been that Federal assistance is provided only when response is beyond State and local capabilities and the State and local governments identify their needs for Federal aid.”²⁶ The National Response Plan (NRP), the successor to the FRP, includes the requirement for State and local resource exhaustion as one of its core concepts.²⁷ The viability of this approach is seriously tested by a large-scale disaster. As Douglas Bair, a member of the Pennsylvania US&R team that responded to Hurricane Floyd, summarized it:

By the time a community is overwhelmed and calls the county for help, the county’s overwhelmed and calls the state, and the state’s overwhelmed and calls the feds, people who might have been rescued if more resources has [sic] been available immediately are already dead.²⁸

Others said as much after Hurricanes Andrew and Katrina. After Andrew, Sen. Bob Graham observed:

²⁵ Committee on Homeland Security and Governmental Affairs, *Hurricane Katrina: A Nation Still Unprepared*, 375.

²⁶ Committee on Environment and Public Works, *Lessons Learned from Hurricane Andrew*, 127-28.

²⁷ U.S. Department of Homeland Security, *National Response Plan* (Washington, D.C.: U.S. Department of Homeland Security, 2004), http://www.dhs.gov/xprepresp/committees/editorial_0566.shtm (accessed 20 March 2006).

²⁸ Rigg, *Pennsylvania to the Rescue*, 2.

For most natural disasters, this procedure [of waiting for State and local resources to be exhausted] makes sense because it maximizes local control of the response effort. But this system assumes that local and State governments will have the ability after the disaster strikes to assess their needs and the extent to which they are capable of responding to those needs. It also assumes that the victims will have their basic needs of shelter, food, medicine, and safety provided for.²⁹

Those assumptions proved ill-founded in both Andrew and Katrina. In both cases, State and local resources were quickly exhausted. Days passed before significant amounts of federal relief supplies began to arrive. The result was the growth of the so-called “gap of pain.” Figure 1 provides a simple visual representation of the concept:

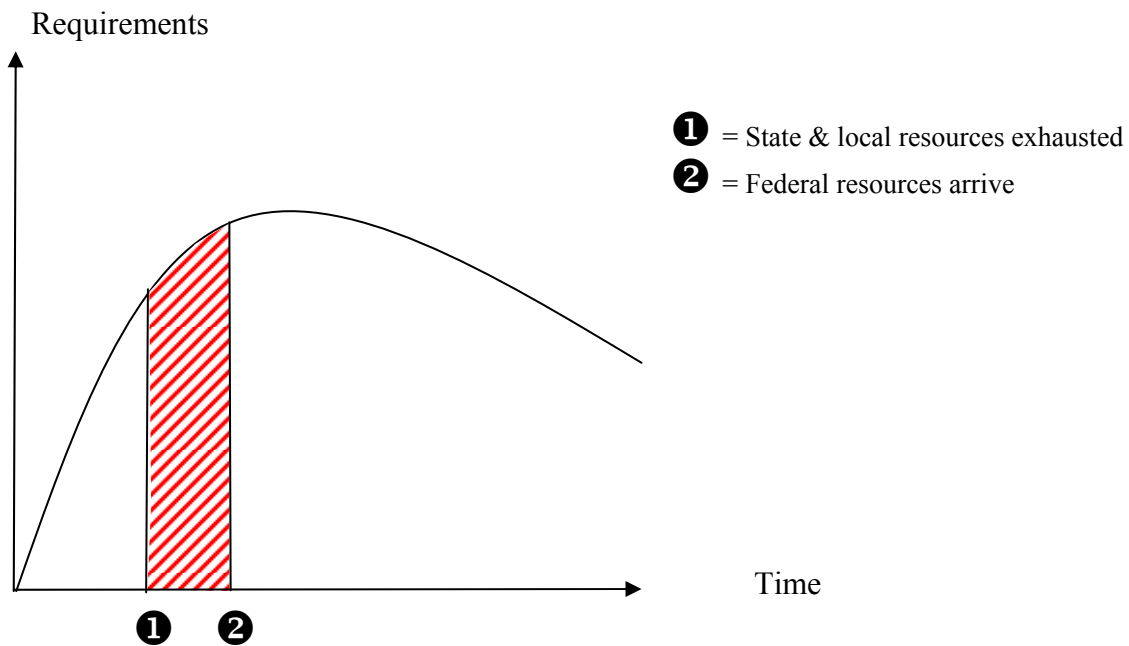


Figure 1. Simple Depiction of the Gap of Pain

The empirical evidence from Hurricanes Floyd, Andrew and Katrina and other major domestic disasters suggests that the gap appears frequently in such situations. The practical consequence of the gap’s emergence is a delay in providing needed goods and

²⁹ Committee on Environment and Public Works, *Lessons Learned from Hurricane Andrew*, 3.

services to survivors, and a commensurate increase in human suffering. The seminal issue is how to close the gap; that is, how to ensure sufficient federal manpower and resources will be available when needed to compensate for the depletion of state and local resources, and will continue to be available through the remainder of the incident response period. The focus of this thesis is an investigation of this question.

Some of the factors influencing the size of the “gap of pain” are outside the control of policymakers, but many are not. Reducing the gap through the application of thoughtful policy changes will mitigate the adverse consequences of an incident for its victims. The missing setpiece in the “story” of disaster response is a coordinated, overarching logistics strategy. In effect, this was also one of the “lessons learned” stated in the report commissioned by the President on the Katrina response.³⁰ Among other things, the White House Report on Katrina recommends that DHS coordinate[s] with State and local governments and the private sector to develop a “modern, flexible, and transparent” logistics system. The objective, according to the report, is to “develop the capacity to conduct large-scale logistical operations that supplement and, if necessary, replace State and local logistical systems by leveraging resources within both the public sector and the private sector.”³¹

The federal government would benefit from examining the private sector for innovations. For several years, the private sector has developed and applied technologically-based logistics management principles to improve the efficiency of commercial supply chains. This new supply chain technology has transformed the logistics function from a peripheral to a strategic one.³² Using a combination of modeling techniques and best practices gleaned from experience, corporations have increased their productivity and improved customer satisfaction. The contrary experience of relief organizations is instructive for the federal sector. Until recently the logistics

³⁰ Frances Fragos Townsend et al., *The Federal Response to Hurricane Katrina: Lessons Learned* (Washington, D.C.: The White House, 2006), 56 (alternately the “White House Report on Katrina”).

³¹ Ibid.

³² Anisya S. Thomas and Laura Rock Kopczak, *From Logistics to Supply Chain Management: The Path Forward in the Humanitarian Sector* (San Francisco, CA: Fritz Institute, 2005), <http://www.fritzinstitute.org/PDFs/Programs/FromLogisticsto.pdf> (accessed 4 October 2006).

practices of these nonprofits were “stuck somewhere in the 1970s or ‘80s.”³³ Now, with the help of commercial logistics experts, some of these best practices have begun to make their way into relief organization logistics planning and execution. Technology has played a significant role in the effort. Indeed, Anisya Thomas, managing director of the Fritz Institute, a humanitarian logistics nonprofit, lists “developing flexible technology solutions” as one of five recommended strategies for improving humanitarian logistics.³⁴ Fritz Institute namesake Lynn Fritz identifies technology as one of the three critical components (along with people and expertise) of an effective logistics system. However, that technology had been all but nonexistent in relief organizations.³⁵ As these organizations have become more technologically savvy, their supply chain functionality and visibility has improved commensurately. The next step is to bring technology to bear to improve the federal disaster relief logistics process. The change cannot come soon enough for disaster victims ill served by extant, *ad hoc* logistics processes practiced by U.S. governmental entities at all levels.

This thesis examines one means of leveraging technology to improve federal humanitarian logistics. Using algorithms from the field of operations research, Capt Ee Shen Tean, a graduate student at the Naval Postgraduate School, has created a strategic decision support model for humanitarian logistics systems. His Pre-positioning Optimization Model (POM) seeks to discover the optimal arrangement of relief supplies and workers in advance of a major incident.³⁶ The outputs of the model provide invaluable insight into the interrelationships between commodities, transportation methods, staging areas, and distribution points. Using this information, planners and decision-makers can test a variety of conditions and scenarios to observe trends, anticipate needs, and identify gaps.

³³ Perry A. Trunick, “Logistics when it Counts,” *Logistics Today*, February 2005, 1, <http://www.logisticstoday.com/sNO/6947/iID/20904/LT/displayStory.asp> (accessed 23 February 2007).

³⁴ Thomas and Kopczak, *From Logistics to Supply Chain Management*, 7.

³⁵ Trunick, “Logistics when it Counts,” 1; Fritz Institute, *Logistics and the Effective Delivery of Humanitarian Relief* (San Francisco, CA: Fritz Institute, 2005), <http://www.fritzinstitute.org/PDFs/Programs/TsunamiLogistics0605.pdf> (accessed 4 October 2006).

³⁶ Ee Shen Tean, “Optimized Positioning of Pre-Disaster Relief Force and Assets” (Master of Science in Operations Research, U.S. Naval Postgraduate School).

Inevitably, any solution based on mathematical models will be somewhat artificial. Such models cannot hope to account for the universe of legal, political, and organizational considerations and constraints, let alone the vicissitudes inherent in the life cycle of a disaster. Optimization models function within boundaries set by programmers and end users. By contrast, the process of providing necessary goods and services to disaster victims takes place in an extraordinarily dynamic and unpredictable environment. One commentator has compared the challenge to “launching D-Day on 24 hours’ notice.”³⁷ The products of a mathematical model always must be assessed for feasibility in light of other relevant factors. For example, the model may conclude that the optimum federal response effort should begin at a time before state and local resources are exhausted. Implementing that approach would require federal statutory authority, most likely an amendment to the Stafford Act.³⁸ Likewise, the optimum theoretical model may have to yield, in whole or in part, to political or fiscal considerations. These elements are outside the scope of this thesis. Similarly, the state and local response is not studied, since it is assumed that Stafford Act conditions precedent have been satisfied; that is, that state and local capabilities have been overwhelmed before the states requested federal assistance.

If the “modern, flexible, and transparent” logistics system advocated by the House committee that investigated the Katrina response were to be implemented, it may be expected that the gap of pain would be reduced. A mathematically-based, stochastic (probabilistic) model of the sort examined in this thesis can be an integral part of that ideal system. Granting the importance of unity of effort to the federal government’s overall disaster response, there are few, if any, major federal agencies that would not benefit from use of the model as a strategic planning tool.

³⁷ Trunick, “Logistics when it Counts,” 1.

³⁸ See generally *Robert T. Stafford Disaster Relief and Emergency Assistance Act*, U.S. Code 42 (1993), § 5121 *et seq.*, as amended by Pub. L. No. 106-390 (2000).

B. CHAPTER OVERVIEW

The remainder of this paper will discuss the current logistics practices in the federal sector, compare four alternative techniques for response, and apply the POM to two hypothetical test cases to assess the viability of the model as a strategic decision-making tool.

Chapter II examines current logistics practices and strategies in the U.S. federal government's planning and execution of disaster response missions. Roles and responsibilities are delineated, and general strategies articulated. Examples are given to illustrate the operation of the system as a whole.

Chapter III enumerates four basic alternatives for rushing commodities and relief workers to the site of a disaster, and evacuating survivors from the area. All four – pre-positioning, proactive deployment, surge transportation, and phased deployment – have been utilized to one extent or another in past disasters. Likewise, all four have both advantages and disadvantages. The alternatives are not exclusive. For any given disaster scenario, it is likely that the optimum logistics process will be some combination of two or more alternatives. The chapter discusses each alternative in turn, then concludes by proposing criteria for evaluating the effectiveness of any particular solution.

Chapter IV introduces the POM as a useful method for evaluating literally tens of thousands of combinations of commodities, relief workers, staging locations, arrival (distribution) sites, and transportation means to arrive at an optimal system. The model's methodology is described, and its assumptions and limitations explained. The utility of the model as a strategic planning tool is tested by applying it to two notional test cases: a one-kiloton (1 kT) explosion of a nuclear device (weapon of mass destruction, or WMD) at Union Station in downtown Washington, D.C.; and a direct strike by a Category 4 hurricane on the Washington, D.C. metropolitan area. For each case, two scenarios are tested, to simulate disasters of lesser and greater magnitude and scope, and to demonstrate the breadth of the model's applicability.

Chapter V reports the findings of the data runs. The POM is used stochastically, and applied against several iterations of budget as an independent variable to produce data spread over a semi-continuous range. In this way, the value of the model to predict

trends and patterns is demonstrated. For the two discrete cases chosen, the results show that Washington, D.C. is well positioned to respond to relatively small- or medium-sized incidents with little need for an all-out, combined governmental and private sector mass response. Conversely, as the scale of the disaster is increased, or encumbrances such as closed roads are introduced, a critical need develops for a combined public-private effort that incorporates commercial cargo capacity. Regarding expenditures, the data reveal a pronounced decline in incremental value gained (at least in terms of survivors saved) as budget amounts increase beyond a determinable level. This finding has significant implications for policy makers trying to achieve the best use of limited financial resources. Notwithstanding the particular findings made from the data used, the more general (and arguably more important) finding is that the POM is a robust tool capable of producing fundamental insights into trends and relationships, over a theoretically unlimited range of possible scenarios.

Chapter VI concludes the thesis by emphasizing the utility of tools such as the POM for future planning and policymaking. The POM is a positive first step, but more development and operational testing is needed.

II. CURRENT PRACTICES AND STRATEGIES

As was the case before Katrina hit, the federal response paradigm today is still relatively *ad hoc*.³⁹ The processes for supplying critical commodities and humanitarian assistance to domestic disaster sites are a jumble of complicated and sometimes contradictory forms, procedures, and unstated conventions operating within stovepiped, inefficient federal bureaucracies. As conceded by the White House Report on Katrina:

The existing planning and operational structure for delivering critical resources and humanitarian aid clearly proved to be inadequate to the task. The highly bureaucratic supply processes of the Federal government were not sufficiently flexible and efficient, and failed to leverage the private sector and 21st Century advances in supply chain management.⁴⁰

Strategies for reducing the gap of pain inevitably must address deficiencies in the existing planning and operational structure. Technologies such as the POM can play an important role. By providing more, and better, predictive data to policymakers, the POM can help drive new strategies to improve the federal government's logistics response to major incidents. Before any new strategy is undertaken, it is instructive to first review the government's current supply chain management processes and strategies.

A. CURRENT FEDERAL LOGISTICS PROCESS

The system in operation during Hurricane Katrina, and largely intact today, relies on a tiered approach. As outlined in the NRP's Logistics Management Support Annex, local jurisdictions must first attempt to fill requirements from their existing resources. Failing that, the local jurisdictions pass on the unfilled requirements to their respective county or State jurisdiction. In turn, the State attempts to fill the requirement. It can do so using its own resources, the resources of other states through Emergency Management Assistance Compacts (EMACs) or mutual aid agreements, or by contracting with

³⁹ J. Michael Barrett and Luke Ritter, "Special Report: DoD Solutions for DHS Problems," *DomPrep Journal: Online Edition* (2006), <http://www.domesticpreparedness.com/index.lasso?pgID-3&arID=1387>.

⁴⁰ Townsend et al., *The Federal Response to Hurricane Katrina: Lessons Learned*, 56.

commercial sources. If the State cannot meet the need, it requests federal assistance from the federal Joint Field Office (JFO) Operations Section.⁴¹ The JFO is the point of entry of a request into the federal process.

Once the JFO Operations Section has received the State's request for assistance, it attempts to satisfy the request from resources available in staging areas. If that is not possible, the requirement is passed to the JFO Logistics Section through Emergency Support Function (ESF) #5 – Emergency Management. Thereafter, the Logistics Section Chief looks to fill the request from one of three sources: (i) resources at the logistics base; (ii) another Federal agency via a formal mission assignment; or (iii) a commercial source, using a requisition form submitted to the JFO Finance/Administration Section. If none of these avenues is successful, the Logistics Section Chief passes the requirement through the Regional Response Coordination Center (RRCC) to the National Response Coordination Center (NRCC). Once there, the request is evaluated by the NRCC to determine how and if it can be met.⁴² If the NRCC identifies a source for the requested resources, it arranges for the resources to be delivered to the location specified by the Logistics Division Chief.⁴³

The NRP anticipates that each NIMS-based organizational element (JFOs, mobilization centers, RRCCs, and the NRCC) will have a separate logistics section. In addition, several other federal agencies have logistics-related roles under the NRP. For example, the General Services Administration (GSA) is the coordinating agency for ESF #7 – Resource Support. In that capacity, the GSA acts as the central procurement authority for the federal government.⁴⁴ It acts on requests from the JFO, the NRCC, and other entities to purchase goods and services to meet requirements. Separately DHS/EPR/FEMA, as the coordinating agency for ESF #5, is responsible for directing the

⁴¹ U.S. Department of Homeland Security, *National Response Plan*, LOG-6; Alane Kochems, *Military Support to Civilian Authorities: An Assessment of the Response to Hurricane Katrina* (Washington, D.C.: The Heritage Foundation, 2005), <http://www.heritage.org/Research/HomelandDefense/bg1899.cfm> (accessed 21 February 2006).

⁴² U.S. Department of Homeland Security, *National Response Plan*, LOG-6.

⁴³ *Ibid.*, LOG-7.

⁴⁴ *Ibid.*, LOG-2-LOG-5.

disposition of all property owned by a federal agency that is used in the disaster relief effort.⁴⁵ Other federal agencies with roles and responsibilities include the Department of Transportation (DOT), as the coordinator of, and contractor for, all transportation requirements under ESF #1 – Transportation; the U.S. Army Corps of Engineers (USACE), responsible for ESF #3 – Public Works and Engineering; and the Department of Health and Human Services, the coordinating agency for ESF #8 – Public Health and Medical Services.⁴⁶

Apart from the many disparate federal agencies with roles in the logistics process, there is a dizzying array of smaller entities with important functions. Within DHS/EPR/FEMA, a separate Mobilization Center is the nominal focal point for pre-positioning, receipt and distribution of supplies. Within DOT a Movement Coordination Center (MCC) manages transportation of response resources to individual mobilization centers and follow-on distribution points.⁴⁷ DHS/EPR/FEMA Headquarters controls movement of these items, through the DHS/EPR/FEMA region with jurisdiction over the disaster site, and in coordination with the DHS/EPR/FEMA Logistics section. DHS/EPR/FEMA Headquarters does not actually determine the best method and source of transportation, however. That responsibility falls to an Emergency Transportation Center (ETC), a sub-unit of ESF #1 within the JFO.⁴⁸

As tangled and convoluted as this process appears, it is only the front end of an even more arcane system. Within federal agencies, other layers of bureaucracy may further slow the delivery of critical commodities to disaster victims. Most notably, the Department of Defense (DOD) has its own requirements for providing logistical support. Unquestionably, the agency which the White House averred “has the capability to play a critical role in the Nation’s response to catastrophic events” is unique in the size and scope of its logistics capabilities.⁴⁹ Yet, even as it holds the tools and the expertise to

⁴⁵ U.S. Department of Homeland Security, *National Response Plan*, LOG-2.

⁴⁶ *Ibid.*, LOG-4.

⁴⁷ *Ibid.*

⁴⁸ *Ibid.*, LOG-3.

⁴⁹ Townsend et al., *The Federal Response to Hurricane Katrina: Lessons Learned*, 54.

deliver supplies and services rapidly, and in unparalleled amounts, DOD is restricted by law and policy from taking a leadership role in domestic disaster response. Homeland Security Presidential Directive 5 speaks of providing military support “as directed by the President or when consistent with military readiness and appropriate under the circumstances and the law.” The NRP and the DOD joint publication on homeland security speak more restrictively of providing support only when local, state and other federal resources are overwhelmed.⁵⁰ In interpreting its role as a supporting agency to another lead federal agency, DOD has created a system that rivals that of the NRP for layers of bureaucracy. Figure 2 below depicts the typical mission assignment process for a request for assistance from civil authorities. There is no provision for a shorter process in emergencies. In fact, the figure below assumes that a major disaster has already occurred, a Defense Coordinating Officer (DCO) is in place at the JFO, and a military Joint Task Force (JTF) has been created to command and control the DOD portion of the response effort.

⁵⁰ U.S. Department of Homeland Security, *National Response Plan*, 42; Department of Defense, *Homeland Security*, Joint Publication 3-26 (Washington, D.C.: Department of Defense, 2 August 2005), IV-1, http://www.dtic.mil/doctrine/jel/new_pubs/jp3_26.pdf (accessed January 2006).

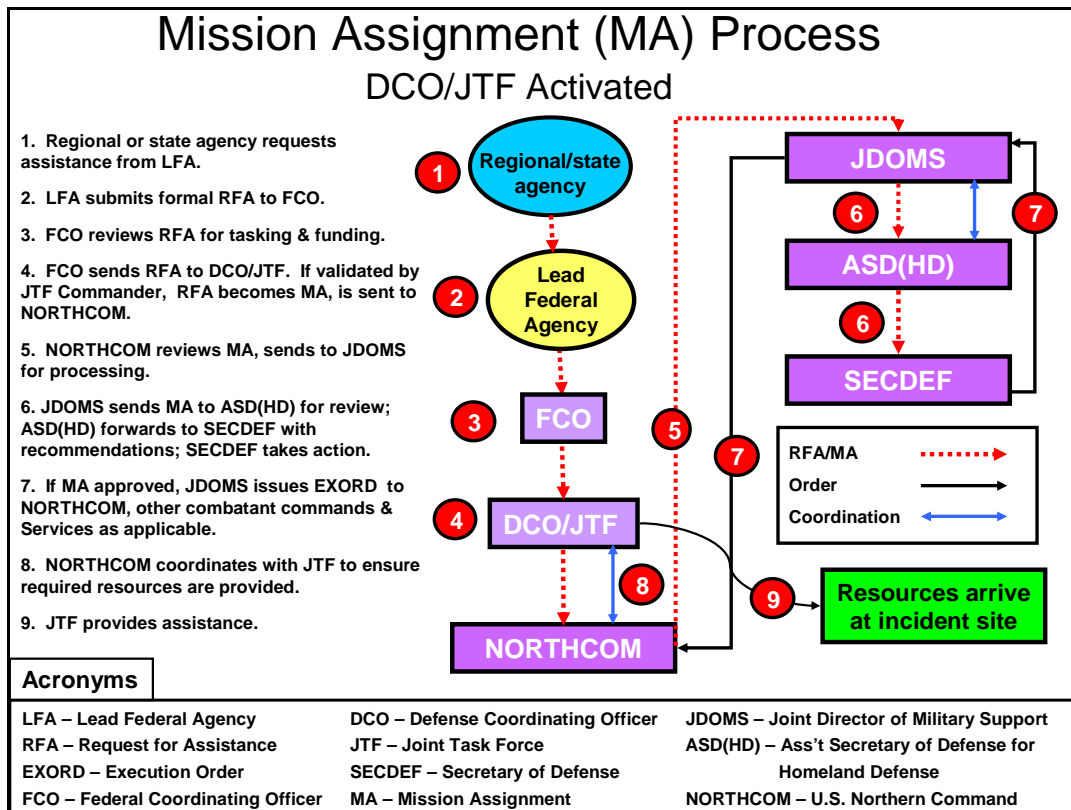


Figure 2. The DOD Mission Assignment Process

The entire discussion *supra* on processing a request for assistance through local, county, State and finally federal officials is subsumed in steps 1 through 3 of the flow diagram in Figure 2. The remaining six steps are particular to DOD. Other federal agencies have their own, unique procedures for processing these aid requests.

If each step represents some increment of time between the local authority's request and the delivery of resources, it is easy to understand why some civilian authorities in Louisiana and Mississippi chose to circumvent the normal procedures for requesting aid, in the interest of expediting deliveries. The House Committee Report on Katrina documents the example of the Louisiana Adjutant General requesting federal military forces directly from the active duty commander, Gen Russel Honoré. The report speculates that the Louisiana Adjutant General's request may have reflected "frustration with the bureaucratic process."⁵¹ Similarly, the White House Report on Katrina found

⁵¹ *House Report on Katrina*, 204.

that even the federal resource managers found it very difficult to determine what resources were needed, what was available, and where the available resources were located at any given time.⁵² In short, State and local authorities encountered a complicated federal logistics system, and predictably responded with a confused patchwork of extra-procedural efforts. Federal authorities, who assumed primary responsibility for the logistics effort when State and local authorities became overwhelmed, had “no clear picture of what was really needed; nor was there clear authority to allow unilateral Federal intervention.” If these conclusions were germane only to Hurricane Katrina, they might be dismissed as the unfortunate, but atypical, results of a once-in-a-century storm. However, they come from the statement of Dennis H. Kwiatkowski, a senior FEMA official, in formal testimony before a Senate subcommittee investigating the federal response to Hurricane Andrew in 1993.⁵³ That so little changed in the intervening twelve years is compelling evidence of the endemic flaws in a system that has endured repeated appeals for its overhaul.

B. FEDERAL POLICIES AND STRATEGIES

The Tenth Amendment to the U.S. Constitution reserves to the States those powers that are not expressly delegated to the United States. This amendment expresses the core organizing principle of a federalist democracy. In the context of disaster response, it is expressed as the fundamental premise that incidents are best managed at the lowest possible geographic, organizational, and jurisdictional level.⁵⁴ This premise is sanctioned in core homeland security strategic documents. For instance, Homeland Security Presidential Directive (HSPD)-5 states:

⁵² Townsend et al., *The Federal Response to Hurricane Katrina: Lessons Learned*, 56.

⁵³ Committee on Environment and Public Works, *Lessons Learned from Hurricane Andrew*, 128-29.

⁵⁴ Richard Weitz, *Federalism and Domestic Disasters: Promoting a Balanced Approach* (Washington, D.C.: Hudson Institute, 2006), http://effss.hudson.org/index.cfm?fuseaction=publication_details&id=3926&pubType=FSS_Reports (accessed April 10, 2006).

The Federal Government recognizes the roles and responsibilities of State and local authorities in domestic incident management. Initial responsibility for managing domestic incidents generally falls on State and local authorities.⁵⁵

The practical consequence of this policy is to compel a tiered approach with State and local authorities as the initial responders. Though nowhere stated formally, the conventional expectation is that communities must be prepared to stand on their own for up to 72 hours after a disaster occurs, before they should expect significant federal assistance to arrive.⁵⁶ Thereafter, as the scope of the disaster broadens, the response gradually escalates until in the most catastrophic events, federal authorities assume the logistics function completely.

Curiously, this tiered approach is exactly what the White House Report on Katrina recommends as the solution for the logistics failures identified in the Katrina response. Specifically, the White House report proposes a four-tiered system: first, State and local resources, preferably pre-contracted; second, State mutual support through EMACs; third, federal assistance to move commodities regionally; and fourth, FEMA supplementation of, or complete substitution for, State and local logistics systems. This proposal differs little from the current system, except for the report's reference to a "fully modern approach to commodity management."⁵⁷

The White House plan amounts to a "pull" system of logistics support. In a pull system, State and local authorities are presumed to know their needs, and to be able to timely articulate them to federal authorities. This system may work well in smaller cases, where States and local authorities are not quickly overwhelmed, or otherwise require only limited federal assistance. It is an abject failure in catastrophic incidents, where State and local resources are almost immediately exhausted, or the State and local governments are

⁵⁵ President, "Directive on Management of Domestic Incidents, Homeland Security Presidential Directive/HSPD-5," *Weekly Compilation of Presidential Documents* 39, no. 10 (February 28, 2003), 281, <http://www.gpoaccess.gov/wcomp/index.html> (accessed 25 October 2006).

⁵⁶ Weitz, *Federalism and Domestic Disasters*, 4.

⁵⁷ Townsend et al., *The Federal Response to Hurricane Katrina: Lessons Learned*, 56.

themselves debilitated or ineffectual. Like most current federal initiatives to improve disaster relief supply chain management, the White House plan is reactive in nature. At its core, it does not address the problem of a fragmented and uncoordinated system.⁵⁸

In contrast to the White House's reliance on a pull system, the House Committee Report on Katrina urges development of a "push" system of logistics support. In a push system, federal assets are moved into a threatened area ahead of a disaster, without waiting for a specific State or local request.⁵⁹ Among other benefits, a push system forecloses situations such as happened in Katrina, where local authorities were too overwhelmed, and their communications abilities too degraded, for a pull system to work.⁶⁰ FEMA used a push system successfully, though on an *ad hoc* basis, in its response to Hurricane Iniki in Hawaii in September 1992.⁶¹ The NRP Catastrophic Incident Annex (NRP-CIA) includes authority for implementing a federal push logistics system when the DHS Secretary has declared an Incident of National Significance and ordered implementation of the NRP-CIA.⁶² The Planning Assumptions contained in the NRP-CIA list indicia of a catastrophic incident. These include:

- The incident may cause large numbers of casualties and/or displaced persons.
- The nature and scope of the incident will immediately overwhelm State and local response capabilities and require immediate Federal support.
- To save lives, prevent human suffering, and mitigate severe damage, the federal response must commence immediately, before receipt of a request via normal NRP channels.
- The incident may cause significant disruption of the area's critical infrastructure, including energy, transportation, telecommunications, and public health and medical resources.⁶³

⁵⁸ Barrett and Ritter, "Special Report: DoD Solutions for DHS Problems," 2.

⁵⁹ *House Report on Katrina*, 136; U.S. Department of Homeland Security, *National Response Plan*, CAT-3.

⁶⁰ *House Report on Katrina*, 324.

⁶¹ *Ibid.*, citing U.S. Gov't Accountability Off., Pub. No. GAO/RCED-93-186, *Disaster Management: Improving the Nation's Response to Catastrophic Disasters*, 2 (July 1993).

⁶² U.S. Department of Homeland Security, *National Response Plan*, CAT-4.

⁶³ U.S. Department of Homeland Security, *National Response Plan*, CAT-3.

Notwithstanding the authority granted in the plan, the DHS Secretary has never invoked the Catastrophic Incident Annex.⁶⁴ Thus, while the legal structure and authority exists to implement push logistics, to date it has not been exercised or implemented.

Arguably one of the most significant differences between a pull system and a push system is in the source and quality of information. The pull system relies on timely and accurate inputs from State and local authorities on the amount and type of aid needed. By contrast, a push system assumes that federal logisticians have forecast the aid requirements in advance. While it might be possible to simply deliver or pre-position large quantities of common commodities to a disaster area ahead of a storm, this approach is both costly and inefficient. Moreover, it is infeasible for situations where there is little or no advance warning, such as a terrorist attack or earthquake.

It is at this point in the process that a stochastic model such as the POM can be leveraged to great advantage. Armed with the supply chain data generated by the model, decision makers will have new ways to create efficiencies. In addition, federal logistics planners will be able to identify persistent shortfalls in, for instance, ramp space, warehouse capacity, or transportation cargo capacity. With this trend information, senior decision makers can take steps to mitigate the shortfalls, whether through the budget process, or through considered shifts in policy or strategy.

To implement national level policies and strategy at the operational level, logistics planners can choose from one or more of four basic options: pre-positioning supplies, deploying assets in advance, “surging” using all available transportation means after the disaster has occurred, or deploying assets in pre-established phases. Each of these alternatives is discussed in detail in the next chapter.

⁶⁴ *House Report on Katrina*, 138.

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III. ALTERNATIVES

In the aftermath of a large-scale disaster, the delivery of supplies and personnel into an affected region is a major undertaking. After Hurricane Katrina swept through the Gulf Coast, the demand for commodities quickly exhausted State and local resources throughout affected areas in Louisiana and Mississippi. Thereafter, federal agencies ranging from the U.S. Department of Agriculture to the U.S. Department of Veterans Affairs mobilized personnel and resources in support of the logistics effort. U.S. Immigrations and Customs Enforcement trucks delivered clothing to evacuees. Department of Agriculture teams with expertise in setting up logistics staging areas, distributing food and removing debris assisted FEMA workers.⁶⁵ One agency alone, the U.S. Department of Transportation (DOT), secured more than 1,600 trucks to deliver more than 25 million Meals Ready to Eat (MREs), 31 million liters of water, 56,400 tarps, 19 million pounds of ice, and 215,000 blankets.⁶⁶

However impressive the final totals, the transition from State to federal logistics responsibility was far from smooth. While the vast resources of the federal government surged to eventually meet survivor demands, the process was slow. As a result, survivors endured extended periods without food, water, shelter or other necessities. Some died, while many others suffered needlessly. Alternatives existed to improve the efficiency and effectiveness of the total response effort. Commodities could have been pre-positioned in advance of the storm. Federal assets could have been deployed sooner, even before the hurricane made landfall. A coordinated, phased deployment of assets leading up to and following the storm's passage could have been executed.

These four techniques – pre-positioning, proactive deployment, surging, and phased deployment – form the basic toolkit for operations planners. Every humanitarian

⁶⁵ “Government Response Activities during the First Three Weeks of the Recovery Effort 27 Sep 2005,” ReliefWeb, <http://www.reliefweb.int/rw/RWB.NSF/db900SID/KHII-6GN3W3?OpenDocument> (accessed 13 February 2007).

⁶⁶ U.S. Department of Transportation, “DOT Activities in Support of Federal Response to Hurricane Katrina,” U.S. Department of Transportation, <http://www.dot.gov/affairs/dot12205.htm> (accessed 21 February 2006).

relief effort uses one or more of these techniques to accomplish the mission. The degree of success of the relief effort will depend on how effectively these four are balanced.

A. EVALUATING THE ALTERNATIVES

1. Pre-positioning

Pre-positioning can be defined as the permanent storage of equipment and supplies near a potential disaster site well in advance of a potential need. The federal government frequently pre-positions necessities such as water and MREs in high-risk areas to shorten response times and facilitate delivery of time critical supplies to distribution points. Pre-positioning is not the same as a push system. Pre-positioned assets still need to be mobilized and deployed to the field. That can happen proactively if the assets are pushed to State or local jurisdictions, or reactively if they are delivered only after a State request.⁶⁷

The Katrina response represented the largest pre-positioning of federal assets in history. FEMA pre-positioned truckloads of water, ice and food at staging locations throughout the southeastern U.S. Figure 3 shows the status of pre-positioned FEMA supplies as of August 29, 2005, when Hurricane Katrina came ashore near New Orleans.

Many of the pre-positioned supplies were stored at Camp Beauregard, a federal staging area in Pineville, LA, well inland from the Gulf Coast. These supplies included 30 truckloads of water, 17 truckloads of ice, 15 trailer loads of MREs, and six trailer loads of tarps. These supplies had been positioned months before in anticipation of the 2005 hurricane season. As Katrina passed over Florida and made its way over the Gulf of Mexico enroute to Louisiana, FEMA did not bring in any additional commodities to Camp Beauregard.⁶⁸ The same pattern was repeated in Mississippi and Alabama. For example, FEMA ordered 400 trucks of ice, 400 trucks of water, and 250 trucks of MREs

⁶⁷ *House Report on Katrina*, 136.

⁶⁸ Committee on Homeland Security and Governmental Affairs, *Hurricane Katrina: A Nation Still Unprepared*, 376.

for delivery to the Naval Air Station in Meridian, Mississippi. At landfall only 30 trucks of water, 15 trucks of MREs, two trucks of tarps, and 30 trucks of ice had arrived.⁶⁹

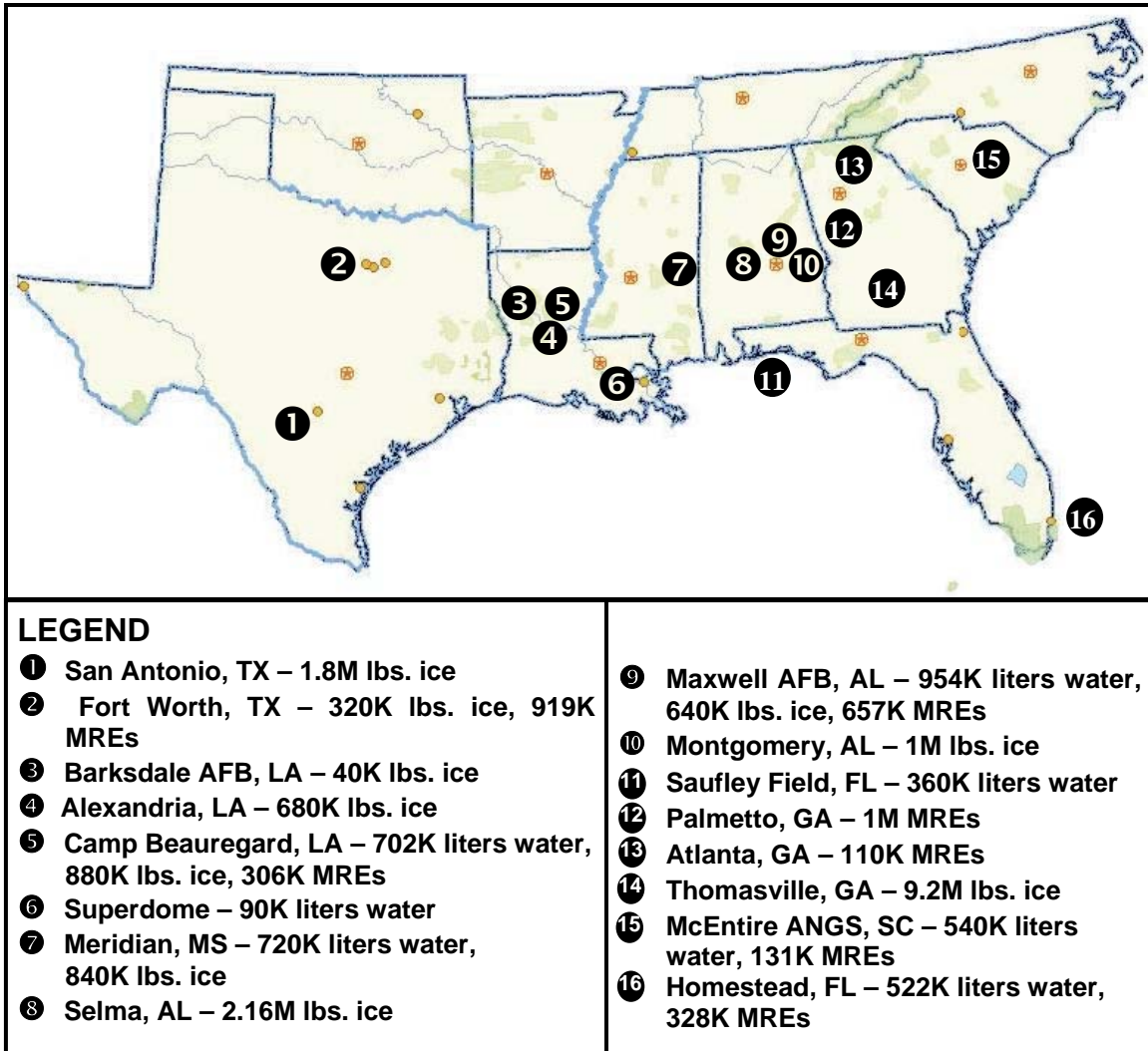


Figure 3. Hurricane Katrina: Federal Commodities on Hand as of August 29, 2005⁷⁰

⁶⁹ Committee on Homeland Security and Governmental Affairs, *Hurricane Katrina: A Nation Still Unprepared*, 376-77.

⁷⁰ After Townsend et al., *The Federal Response to Hurricane Katrina: Lessons Learned*, 30.

After Katrina struck, the pre-positioned supplies quickly ran out. This illustrates one of the weaknesses of reliance primarily on pre-positioned supplies: requirements estimates must be quite accurate, or critical shortfalls quickly develop. Once that happens, it is difficult for the logistics system to catch up in the short term.

The pre-positioning method suffers from other weaknesses as well. Leasing or buying warehouse space can be expensive. Perishable supplies cannot be stored for long periods. Some items, such as medicines, must be stored in controlled conditions. Choosing storage locations can be problematic: Too close to the affected area, and there is significant risk that the supplies will be caught up in the disaster and degraded or lost. Too far away, and supplies cannot be transported to the disaster zone quickly enough. Without an asset tracking system, pre-positioned supplies can be diverted or lost. This happened in Katrina, where pre-positioned federal assets destined for local hospitals were never received.⁷¹

There are advantages to pre-positioning equipment and supplies. Certain commodities, such as water, MREs, and medical supplies will be required in nearly all disaster scenarios. At least some of these “stock” supplies can be stored virtually indefinitely. Bottled water, tarps and cots are all examples. Although needs estimates may be inaccurate, extra supplies may be stored as a buffer against unforeseen circumstances (though this will increase storage costs). Finally, pre-positioning supplies effectively shortens the supply chain, leaving less chance for delivery delays.

The federal government has recently placed additional emphasis on pre-positioning in its planning and preparation for future major hurricanes. In advance of the 2006 hurricane season, FEMA dramatically increased its stockpiles of relief supplies. According to the official web site of the Office of the [U.S.] President, DHS stockpiled four times the MREs and ice and 2.5 times the water as what it had available prior to Hurricane Katrina. The web site claims that the pre-positioned supplies have the capacity to sustain one million people for a week.⁷² Of course, having adequate stocks of supplies

⁷¹ *House Report on Katrina*, 326.

⁷² “Hurricane Preparedness,” Office of the President, <http://www.whitehouse.gov/infocus/hurricane/> (accessed February 2007).

in warehouses close to the disaster area is only part of the process. There must be quick and efficient means to transport the supplies from the staging areas to points of distribution within the disaster zone.

2. Proactive Deployment

Proactive deployment is synonymous with push logistics. The concept is analogous to pre-positioning, but on a different timetable. Pre-positioning is done without consideration of a specific threat, while proactive deployment is done in response to a pre-existing threat or event. The supplies stored at Camp Beauregard in early 2005 were pre-positioned months before Hurricane Katrina threatened the Gulf Coast. In proactive deployment, additional supplies, equipment and personnel are transported to staging sites near the projected disaster area usually no more than a few days in advance.

The great advantage of proactive deployment is that it takes place under conditions of good, albeit imperfect, information. Whereas pre-positioning is done based on such factors as historical risk, proactive deployment is intended to prepare an area to respond to a known threat or condition. Accordingly, the deployed “package” can be more closely tailored to anticipated needs. If the threat is a flood, swift water rescue teams and equipment and sandbags will be a priority. If the threat is a volcanic eruption, for instance Mount St. Helens, the pre-deployed package might include burn treatment medicines and specialized burn treatment medical teams. In addition, the quantities of goods and relief services required can be estimated much more accurately, resulting in a more efficient distribution of commodities and relief workers. Proactive deployment also has the advantage of minimal storage costs, relative to the pre-positioning option.

On the negative side, deploying assets proactively in a matter of days still requires a significant commitment of the transportation means, as well as the workers and supplies themselves. This is particularly true for specialists, such as trauma physicians. Pre-deploying this group in anticipation of a hurricane that never makes landfall wastes valuable resources and incurs substantial costs. Likewise, push logistics is unavailing for unanticipated incidents such as terrorist attacks or tsunamis. It is also of marginal utility

if not accompanied by adequate pre-planning. Misjudging the volume of commodities that will be needed to supply an affected region, and the expected duration of the relief effort, can result in a severe resource gap and increased human suffering.

3. Surge Transportation

Surge transportation assumes that no commodities or workers are pre-positioned prior to an incident. After the fact, all available transportation methods are mobilized and employed to supply the affected area. To a degree, surge methods were used in responding to Hurricane Katrina. Assets from across the federal, State and local governments were brought to bear. These included non-traditional transportation sources, such as U.S. Department of Agriculture trucks delivering food and baby formula, and National Guard helicopters airdropping MREs, water and ice into areas isolated by debris fields.⁷³ About a dozen commercial airlines and contract carriers also assisted, but only after DHS Deputy Secretary Michael Jackson called Air Transport Association president Jim May asking for help. There were no pre-existing contracts in place for air support.⁷⁴

Since proactive deployment cannot be used in situations where the disaster is sudden and unexpected, surge transportation may be required. Terrorist attacks are an obvious example. As the Katrina experience showed, this method is not as well suited for times where advance notice is available, notably hurricanes, floods, and other slow-developing disaster scenarios.

Surge transportation is the most reactive of the four approaches. It is analogous, but not identical, to a pure “pull” logistics system. Pull logistics is defined by the requirement that customers (in disasters, State and local authorities) must request the goods or services to be provided. Only when a request is received will the provider begin shipping. In contrast, federal authorities may begin surge deliveries of supplies and relief workers to a disaster zone without a State or local request. This can occur if it is apparent that State and local governments have broken down, or are overwhelmed.

⁷³ *Government Response Activities during the First Three Weeks*, 2-3.

⁷⁴ *House Report on Katrina*, 123.

At its most robust, surge transportation is characterized by strong public-private partnerships that give government responders ready access to commercial means of transportation. There is precedent for these sorts of arrangements. The Civil Reserve Air Fleet (CRAF) and the Voluntary Intermodal Sealift Agreement (VISA) are DOD programs which co-opt private sector assets on minimal notice to meet critical military mission requirements. DHS has no functional equivalents. However, it could adopt the CRAF and VISA programs as models to develop its own arrangements with commercial air cargo, freight, sealift, and rail transport companies.⁷⁵

The advantages of creating such programs are manifest. By using private sector assets pursuant to pre-established agreements like the VISA, the federal government would be leveraging the latest advances in commercial supply chain management. It also would be, in effect, substantially increasing the size of its transportation force immediately upon activation of the relevant agreement. A less obvious advantage is in cost savings. In the Katrina response, there was ample evidence of “on the fly” government purchasing and contracting at costs well above market rates.⁷⁶ These excesses would be largely avoided if the federal government had pre-established rates and requirements with domestic carriers. Two of the major after-action reports on Katrina – the White House report and the House Committee report – recommend that DHS enter into such pre-established contracts for the provision of goods and services during emergencies.⁷⁷ The House Committee report expressly recommends consideration of a CRAF program to provide commercial air support to future relief efforts.⁷⁸ To its credit, DHS appears to be making progress on this front. In advance of the 2006 hurricane season, DHS Secretary Chertoff told a National Emergency

⁷⁵ Barrett and Ritter, “Special Report: DoD Solutions for DHS Problems,” 2; Perry A. Trunick, “Fading into a Bad Dream,” *Logistics Today* 46, no. 10 (October 2005), 10-11.

⁷⁶ Barrett and Ritter, “Special Report: DoD Solutions for DHS Problems,” 2.

⁷⁷ *House Report on Katrina*, 5, 329-331; Townsend et al., *The Federal Response to Hurricane Katrina: Lessons Learned*, 56.

⁷⁸ *House Report on Katrina*, 123.

Management Association conference that the agency was ending the former practice of entering into *ad hoc* trucking contracts through DOT. According to Secretary Chertoff, in the future such contracts will be pre-arranged.⁷⁹

4. Phased Deployment

“Phased deployment” is the fourth basic method of supplying goods and services in a disaster response. It is not a term of art; in fact, it is not an approach recognized by government planners. Rather, the approach is the author’s adaptation of the Just-in-Time (JIT) production philosophy commonly found in commercial supply chain management

The essential premise of JIT is that supply chains can become more efficient by scheduling the materials, supplies and even services needed for production so that they arrive just when they are needed. Among other benefits, this saves warehousing costs by minimizing excess inventory. The impact can be tremendous. For example, in the early 1980s Ford’s shift to a JIT system reduced its inventory holding costs by 33%, for a total savings of three billion dollars.⁸⁰

While Just-in-Time systems are perfectly suitable for some commercial supply chains, JIT suffers too many major flaws to make it broadly feasible for disaster relief. In the context of emergency response, a disaster relief supply chain built solely on JIT principles stands a good chance of failing. JIT systems do not cope well with change, in particular changing demand rates. JIT tends to be a pull system which does not anticipate customer demand; in the words of one author, “JIT doesn’t plan well.”⁸¹ In addition, JIT relies on a steady inventory stream. The flow can be disrupted by flooding, earthquakes, labor strikes, or any number of other impedances.⁸² Adequate human capital is a

⁷⁹ *DHS Vows to Reform Disaster Response*, 9.

⁸⁰ Bob Freitag and Fred Savaglio, *Just in Time Inventory: Effects on Earthquake Recovery* (Seattle, WA: Cascadia Region Earthquake Workgroup, 2005), <http://www.crew.org/papers/JITfinal032405.pdf> (accessed 22 February 2006).

⁸¹ Tony Polito and Kevin Watson, *Just-in-Time Under Fire: An Exploratory Investigation Identifying Major Reservations regarding Improvement through JIT Philosophy*, 2006), www.tonypolito.com/wri_jitf.doc (accessed 22 February 2006).

⁸² Freitag and Savaglio, *Just in Time Inventory*; Polito and Watson, *Just-in-Time Under Fire*, 2-3.

prerequisite to the success of JIT systems.⁸³ However, after a disaster strikes, workers' personal concerns frequently outweigh their motivation to report to work. This was very publicly demonstrated in media reporting of the New Orleans Police Department's high rate of absenteeism after Hurricane Katrina struck.

While a "pure" JIT supply chain would be inappropriate for disaster response, some of its features merit consideration by government planners. JIT assumes that requirements can be predicted in advance. Using optimization algorithms, corporations backtrack from a set of given requirements to determine the most efficient flow of pre-production components to the manufacturing facility. To borrow a military term, this is a tactical solution. If disaster relief requirements could be predicted with reasonable precision, it would seem to be possible to apply the same optimization methodology to arrive at an "ideal" stream of goods and services to a disaster site.

Phased deployment, a modification of JIT, may have applicability for some types of incidents. There are circumstances where the effects of, and therefore the response requirements for, a specific scenario can be modeled with some precision. This paper uses one such scenario, a one-kiloton nuclear detonation in an urban area. To the extent that information on requirements is available, and somewhat static, logistics planners could create plans which match commodity flows more precisely to victims' needs at particular points in time in the recovery process. Even if phased deployment cannot be used at the tactical level, it may have utility as a strategic tool. Assuming a stochastic model, i.e. with random variables, it should be possible to derive strategic conclusions from the results of repeated data runs using a wide range of hypothetical scenarios.

B. TOWARD AN OPTIMAL SOLUTION

Depending on the scenario and the quality of information known in advance, any of the four alternatives may be the best approach. In most cases, a combination of methods will yield the most efficient solution.

⁸³ Polito and Watson, *Just-in-Time Under Fire*, 2-3.

Figure 4 graphically illustrates the fundamentally different approaches used by the four methods to supply commodities and workers to an affected area.

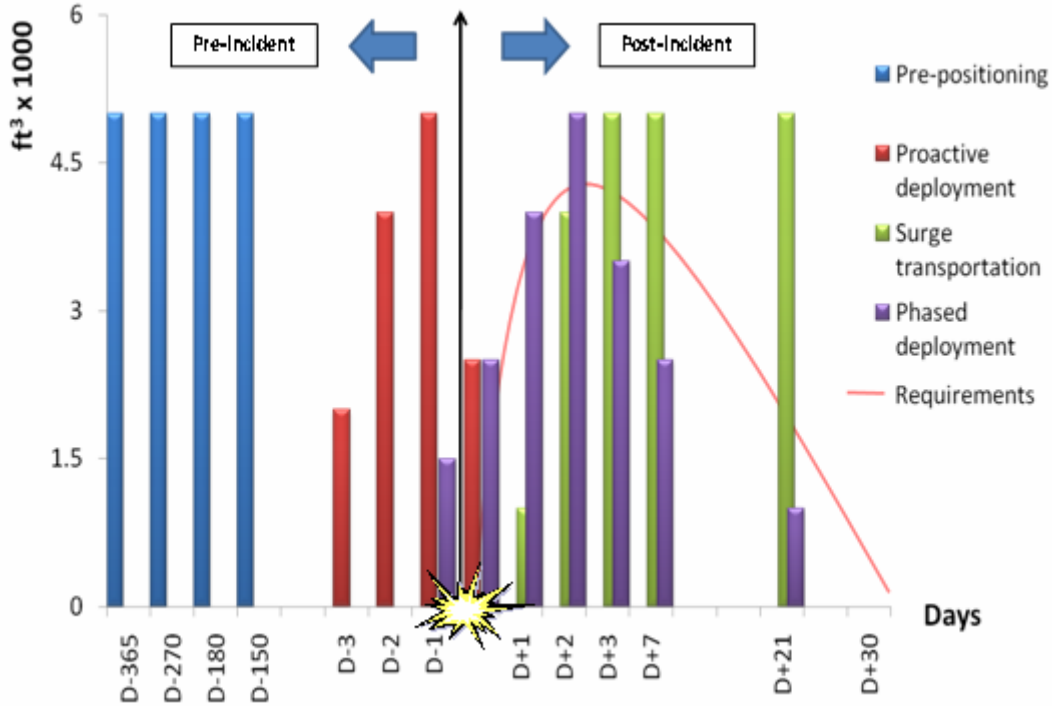


Figure 4. Comparison of Disaster Relief Supply Alternatives

The chart’s vertical axis represents the volume of supplies delivered. For purposes of the notional chart, a maximum daily delivery capacity for the entire logistics system of 5000 cubic feet ($\text{ft}^3 \times 1000$) is assumed. The horizontal axis represents the timeline of the disaster, backward one year and forward one month from the date of the incident (“D” day). Note that the horizontal axis is not to scale; it has been compressed for clarity. The colored bars represent volumes of commodities delivered on a given day using a specific method. The skewed red curve on the “post-incident” side of the chart represents a typical pattern of commodities requirements following a disaster: steep at first, peaking some days after the incident, then tapering off over a period of weeks.

The overarching objective is to “fill in the bubble”; that is, to deliver relief supplies and workers at such a pace and in such quantities as to completely satisfy requirements for the duration of the response. Bars outside the curve represent

inefficiencies and excess costs – warehousing costs, supply chain backlogs, and the like. Gaps between bars under the curve and the curve itself represent needs unmet at that time. Supplies may be available, for instance if they have been pre-positioned, but they were not delivered at the time they were needed.

The chart offers a basis for comparison of the four supply alternatives. The most obvious difference between the methods is temporal. As the chart shows, pre-positioning takes place well before the incident occurs. Proactive deployment starts when the threat is identified, usually only a few days before the threat actually materializes, and ends when the incident occurs. Surge transportation starts immediately after the incident occurs, but takes a while to ramp up to maximum system capacity. Phased deployment attempts to match the requirements curve, tailoring deliveries to identified needs.

Another point of comparison is the relationship of the alternatives to the requirements curve. Because they occur so far in advance, flows of supplies to be pre-positioned are not tied to the requirements curve. Therefore, the only information the planner needs to know is the total amount of commodities needed, not their distribution. The same could be said of proactive deployment, though since it takes place immediately prior to the incident, there is less opportunity to make up shortfalls. Accordingly, logisticians planning proactive deployments need to have some sense of the requirements distribution, so they can plan to cover any shortfalls as soon after the incident as possible. Surge transportation, the pull system analogue, correlates to the requirements curve only imperfectly. By its nature, surge transportation will almost always be a step behind requirements. As additional layers of bureaucracy are introduced, and State and local authorities' ability to submit requests is diminished, the surge curve shifts to the right, becoming progressively distant from the requirements curve. Phased deployment comes closest to matching the requirements curve. Given a static post-disaster environment, phased deployment is clearly the preferred method. But, neither Mother Nature nor terrorists are that cooperative. Shifting winds, downed power lines, and damaged roads, bridges and other infrastructure wreak havoc with phased deployment plans.

By itself, none of these alternatives is sufficient. Simply put, humanitarian logistics is just too unpredictable. One expert has commented that “the supply chain for

relief is the ultimate sense-and-respond supply chain.”⁸⁴ In other words, disaster logistics will always occur in an environment of variable demand and uncertainty. In the military context, this is often referred to as the “fog of war,” from von Clausewitz:

The great uncertainty of all data in war is a peculiar difficulty, because all action must, to a certain extent, be planned in a mere twilight, which in addition not infrequently — like the effect of a fog or moonshine — gives to things exaggerated dimensions and unnatural appearance.⁸⁵

There is no absolute remedy for the inevitable uncertainty and complexity attendant with operating a disaster relief logistics system. However, there are remedial measures that can, and should, be taken. Foremost among these, at least for purposes of this thesis, is the development of flexible technology solutions. Anisya Thomas of the Fritz Institute lists this among five strategies for humanitarian aid agencies to adopt to improve their operations. Although her advice was intended for nongovernmental relief organizations, it is equally persuasive for the public sector. According to Ms. Thomas, “Despite the complexity of humanitarian logistics, manual processes still dominate and IT resources that could enhance information availability, reporting and learning are often not effectively leveraged.”⁸⁶

The stochastic optimization model discussed in the remainder of this paper offers a practical, strategic level technology solution of the sort advocated by Ms. Thomas. Using real-world data, the POM can give logistics planners and senior policymakers visibility of the supply pipeline for a particular incident and location. It is also a learning tool. As it is applied to a variety of scenarios and under a range of conditions, it will provide insights into relationships, capabilities, and potential shortfalls. Although not a panacea, the POM is a worthy first effort to model disaster relief supply chains in ways that are useful to operators and decision makers.

⁸⁴ Thomas and Kopczak, *From Logistics to Supply Chain Management*, 79.

⁸⁵ “Fog of War,” Wikimedia Foundation, Inc., http://en.wikipedia.org/wiki/Fog_of_war (accessed 28 February 2007).

⁸⁶ Thomas and Kopczak, *From Logistics to Supply Chain Management*, 12.

IV. THE STOCHASTIC OPTIMIZATION MODEL

A. MODEL DESCRIPTION

The Pre-positioning Optimization Model (POM)⁸⁷ is a two-stage, linear, mixed-integer program that endeavors to calculate the placement and employment of relief units and assets to achieve the most efficient supply distribution network. The program is written in open source code using the General Algebraic Modeling System (GAMS).⁸⁸ Data sets are solved using ILOG's CPLEX, a high-performance software program for solving large-scale mathematical optimization problems.⁸⁹

The model employs linear, mixed-integer programming. Regarding the former, the POM assumes that the variables in the model are related to each other linearly. Linear programming is a mathematical technique dating back to World War II, when George Dantzig, a RAND Corporation mathematician, developed the Simplex Method to solve military logistics problems. Its power comes from its ability to solve a wide array of complex problems quickly and efficiently. A linear programming problem is characterized by a linear objective function of some discrete number of real variables subject to a number of linear constraints.⁹⁰

The "mixed-integer" part of the model description refers to the expression in whole numbers of some decision variables, for example, the number of aircraft and trips made.⁹¹ In mathematical terms, solving this optimization problem involves maximizing a linear function of many variables subject to linear constraints, where one or more variables must be integral.⁹² Here, the constraints include parameters such as total

⁸⁷ Tean, *Optimized Positioning of Pre-Disaster Relief Force and Assets*.

⁸⁸ See generally Anthony Brooke et al., *GAMS: A Users Guide* (Washington, D.C.: GAMS Development Corporation, 1998).

⁸⁹ "ILOG CPLEX: World's Leading Mathematical Programming Optimizers," ILOG, Inc., <http://www.ilog.com/products/cplex/> (accessed 1 March 2007).

⁹⁰ Steven Nahmias, *Production and Operations Analysis*, 5th ed. (New York, NY: McGraw-Hill/Irwin, 2005), 154.

⁹¹ Tean, *Optimized Positioning of Pre-Disaster Relief Force and Assets*, 14, 17.

⁹² Laurence A. Wolsey and George L. Nemhauser, *Integer and Combinatorial Optimization* (New York, NY: John Wiley & Sons, Inc., 1999), 3-4.

budget, maximum number of units of transportation means (TMs) available, maximum space available on each TM, and maximum expansion capacity for ramps, warehouses and medical facilities. The reader is referred to Captain Tean's thesis for a more complete description of the constraints.

The model is stochastic, two-stage⁹³ in the sense that it explicitly incorporates uncertainty by examining the logistics network from two perspectives, strategic and operational. POM outputs particular to the first (strategic) stage include recommendations to expand warehouses, health care facilities, and ramp space, as well as the recommended number of health care personnel to care for survivors. These are all strategic decisions that will take years to implement. The second (operational) stage takes a shorter, scenario-dependent view. Here, the model represents the humanitarian logistics system as a functioning network, and examines its operation over the course of a 72-hour period immediately following a major incident. Second-stage parameters include the number of potential survivors (PS) and commodity demand at each affected area (AA),⁹⁴ as well as the accessibility of each AA using each of the defined TMs.⁹⁵

The two views are related by the concept of "recourse," defined as the ability to take corrective actions after an uncertain event has taken place. In the strategic stage of the model, decisions are made about expanding warehouses, medical facilities, and ramp space. The goal is to maximize the expected number of rescued survivors based on those decisions, across a range of random values for the second-stage variables. In the operational stage, the model incorporates the decisions made in the first stage, and optimizes the commodity distribution process for each defined scenario in order to maximize rescued survivors for that scenario. To encourage the model to prioritize commodity deliveries, the data includes a penalty of ten survivors per thousand cubic feet

⁹³ See generally John R. Birge and Francois Louveaux, *Introduction to Stochastic Programming* (New York, NY: Springer Science & Business Media, 1999).

⁹⁴ For ease of cross-referencing, this paper adopts the terms defined by the original POM creator in his thesis. "PS" and "AA" are examples. The reader is referred to the original work for clarification and definition of terms not otherwise explained herein. See Tean, *Optimized Positioning of Pre-Disaster Relief Force and Assets*.

⁹⁵ For instance, in this thesis it is assumed that among the aviation assets, only helicopters and vertical/short takeoff and landing (VSTOL) aircraft could land at affected areas without runways.

of undelivered commodities.⁹⁶ The random nature of the second-stage parameters renders the solution stochastic, hence the description of the mathematical process as a two-stage stochastic optimization problem.⁹⁷

The POM is flexible enough to accommodate transportation means in all three domains – air, land and sea. Aircraft, helicopters, trucks, buses, and ships are all valid TMs in the POM. Thus, the model can yield relevant insights for circumstances ranging from the 2004 tsunami in Southeast Asia, where commodities had to be airlifted or sealifted to island-based survivors, to the 2005 Pakistani earthquake, where sealift was not an option. Likewise, since budget is accounted for as a constraint in the model, the POM is equally useful for jurisdictions with very modest amounts to spend on emergency preparedness and response, such as small- or mid-sized cities, or for national-level governments or agencies with emergency management budgets in the many millions or billions of dollars, such as the U.S. Department of Homeland Security. The POM is also robust in its accommodation of different types of commodities staging locations (relief locations, RLs, expressed in the POM as l_x) and arrival locations (AAs in the POM, expressed a_x). RLs can be land terminals such as a motor freight hub, air terminals such as the UPS Worldport air cargo operation at Louisville (KY) International Airport, or seaports such as the Port of Long Beach near Los Angeles.

B. METHODOLOGY

This section explains the methodology employed to test the POM against two hypothetical, but realistic, major incidents. The two hypothetical incidents simulate one natural disaster and one terrorist attack, respectively, both occurring in the National Capital Region. Both are discussed in greater depth in Section C *infra*. The first part of

⁹⁶ Data for the original POM model are expressed in tons. However, professional logisticians interviewed for this thesis stated that the more common measure of cargo carrying capacity is volume. Accordingly, data used for this thesis is uniformly expressed in thousands of cubic feet ($\text{ft}^3 \times 1000$). E.g., Matthew Trachtman (Manager and Logistics Planner, Transgroup Worldwide Logistics), interview by author, Dulles, VA, November 20, 2006.

⁹⁷ Tean, *Optimized Positioning of Pre-Disaster Relief Force and Assets*, 6.

this section describes the data used in the test cases, and their derivation. The second subsection lists the most significant assumptions made, as well as limitations on the model's use and the results obtained.

1. Data Used

The data used in the two test cases were obtained through a combination of publicly available information and interviews with logistics specialists, airport officials and other subject matter experts. Where direct data were not available, attempts have been made to derive reasonable approximations based on best available information.

The POM uses 15 different files to store the data needed for the model. These may be generally described as follows:

- Five data table files on AAs, RLs, TMs, potential survivors (PS), and commodity requirements
- Five data definition files, defining the set of AAs, RLs, TMs, scenarios (ωx) for each test case, and the miscellaneous data parameters
- A file for holding miscellaneous data, including budget, survivor penalty for undelivered commodities, and number of survivors attended per health care worker
- Data on the number of workers per thousand cubic feet of commodities required under each scenario
- A file to specify feasible RL departure points for all TMs
- A table of enroute times for TMs from RLs to AAs
- For each AA, a list of TMs that require ramp space

The data are organized into five major sets: transportation means, demand for each commodity type (workers and survivors), affected areas, relief locations, and other data, such as budget and penalty for undelivered commodities.

a. Transportation Means

The POM was originally tested with three TMs – the CH-53 helicopter, the MV-22 VSTOL aircraft, and the HMMWV (colloquially, the “Humvee”) military vehicle. For this thesis, the number of TMs has been expanded considerably to include a

broader sampling of military airlift aircraft, as well as the most commonly used commercial cargo aircraft, and some ubiquitous forms of ground transportation, such as passenger buses and tractor-trailers.

Appendix A summarizes the TM data used in this thesis. Data on CH-53 and MV-22 availability are assumed, consistent with Captain Tean's research. For C-130 and C-17 military cargo aircraft, it is assumed that one full squadron of each are available, with another half-squadron in reserve. The commercial cargo aircraft represent the most common aircraft in the United Parcel Service (UPS) and Federal Express (FedEx) fleet.⁹⁸ For the commercial cargo aircraft (B747, DC-10, A300, and MD-11), it is assumed that 20% of the UPS and FedEx fleets are available. The Civil Reserve Air Fleet (CRAF) minimum of 15% of a carrier's fleet is used as a benchmark. This percentage relates almost exclusively to international flights, since the primary CRAF mission is military airlift to deployed locations overseas.⁹⁹ To reflect the somewhat easier circumstance of mobilization in support of domestic disaster relief, the 15% figure is adjusted upward slightly, to 20%. The total of 56 tractor trailers, box vans and passenger buses assumes that FEMA has activated all 28 federal US&R task forces, as happened after Hurricane Katrina. Each US&R team typically travels with two each tractor trailers, box vans and passenger buses.¹⁰⁰ The maximum expansion for these ground TMs is estimated based on the availability of government and commercial sources in or near the National Capital Region, the site of the hypothetical incidents.

Survivor capacity refers to the capability of the TM to carry survivors away from the disaster zone. The numbers have been gathered from publicly available data on the passenger capacity (if any) of each TM, taking into account the type of mission of each. Thus, the general purpose CH-53 and MV-22 are assumed to be

⁹⁸ "About FedEx: FedEx Express Facts," Federal Express Corp., <http://www.fedex.com/us/about/today/companies/express/facts.html?link=4> (accessed February 2007); "Federal Express Airfleets: Fleet Listing," Airfleets.net, <http://www.airfleets.net/flottecie/Federal%Express.htm> (accessed February 2007).

⁹⁹ "Civil Reserve Air Fleet," Wikimedia Foundation, Inc., http://en.wikipedia.org/wiki/Civil_Reserve_Air_Fleet (accessed February 2007).

¹⁰⁰ Kenneth Wright (Logistics Manager, TX-TF1 Urban Search & Rescue Team), telephone conversation with the author, November 2006.

carrying workers and commodities, not survivors. The same is true of all cargo aircraft and cargo vehicles. The rescue CH-53 and MV-22 capacities are based on the maximum number of litter patients the aircraft can carry. The passenger bus is able to evacuate a full load of ambulatory survivors, once it disgorges its US&R workers at the disaster site.

Worker capacity refers to the number of relief workers that can be carried. Here, the data reflects the assumption that the general purpose CH53 and MV-22, the C-130J, and the C-17 are configured to carry nothing but passengers. The same is assumed of the B747, the only cargo aircraft in the group routinely retrofitted to carry passengers. The tractor trailer and the box van carry a small number of workers (three each) in the main cab. The passenger van can carry a full complement of workers to the affected area.

The POM is self-limited to examining the 72-hour period immediately after a disaster strikes. Therefore, the three-day hours available represents the maximum number of hours in the observed period that a TM will be available for use. Note that this does not indicate projected flight time for aircraft in the period, or travel time for ground TMs. Instead, it acts as an outer boundary on the model's use of the TM. The figures for aircraft operating range have been obtained from publicly available sources. Where an operating range is not available, as for the B747, it is calculated by dividing the maximum effective range of the aircraft with a full cargo load by the cruise speed. The hours available for ground TMs are premised on the standard US&R practice of at least two drivers per vehicle, with minimum stops enroute. Operating range for ground vehicles is based on a single tank of gas.¹⁰¹

The POM uses variable expansion cost (*vec*) to determine whether a portion of the budget should be spent on more TMs. Calculating the *vec* proved challenging. Replacement cost is often an unrealistic measure. For commercial cargo aircraft, for example, the federal government is not going to purchase another B747 for FedEx or UPS at a cost of \$200 million. Rather, the standard practice in the industry is to enter into ACMI (aircraft, crew, maintenance and insurance) contracts with carriers.

¹⁰¹ Kenneth Wright (Logistics Manager, TX-TF1 Urban Search & Rescue Team), e-mail message to author, 15 November 2006.

Under an ACMI lease, the carrier provides all of the basics required to fly the airplane – the crew, routine maintenance, insurance, and the aircraft itself. In a typical ACMI lease the contracting party, in this case the federal government, pays for fuel, landing fees, customs fees, and the like.

This thesis assumes a 100-hour (minimum) ACMI lease for all aircraft variable expansion cost calculations. Table 1 contains the results of the variable expansion cost calculations, using both replacement cost (RC) and block hours (BH) as separate bases for the calculations.

Aircraft	Replacement Cost (\$)	Block Hour Rate (\$/b.h.)	Cargo Capacity (ft ³ x 1000)	Variable Expansion Cost (vec)(\$)(RC)	Variable Expansion Cost (vec)(\$)(BH)
C-130J ¹⁰²	48,000,000	3,200	4.551	10,657,000	70,314
C-17 ¹⁰³	202,300,000	15,280	8.736	23,157,000	174,908
B747 ¹⁰⁴	200,000,000	15,761	6.190	32,310,000	254,620
DC-10 ¹⁰⁵	88,400,000	12,800	4.618	19,142,000	277,176
A300 ¹⁰⁶	90,000,000	8,227	13.822	6,511,000	19,896
MD-11 ¹⁰⁷	101,660,000	14,000	21.100	4,815,000	66,350

Table 1. Aircraft Expansion Costs Calculations – Replacement Cost vs. ACMI

¹⁰² “C-130J Specifications and Performance,” GlobalSecurity.org, <http://www.globalsecurity.org/military/systems/aircraft/c-130j-specs.htm> (accessed February 2007).

¹⁰³ Major Paul E. Boley II and Major David L. Lyle, “Afloat Prepositioning,” in *Today’s Logistics: Selected Readings and Analysis*, ed. James C. Rainey, Beth F. Scott and Gail Waller (Gunter Annex, Maxwell AFB, AL: Air Force Logistics Management Agency, 2001), 33, http://www.aflma.hq.af.mil/lgj/todays_logistics.pdf (accessed February 2007); Duane H. Cassidy et al., *Commercial Application of Military Off Airlift Aircraft*, <http://www.pogo.org/m/cp/cp-HeavyLifting-AppendixB-CAMAA.pdf> (accessed February 2007).

¹⁰⁴ *Atlas Air Worldwide Holdings, Inc. Reports Second-Quarter 2006 Results* (Purchase, NY: Atlas Air Worldwide Holdings, Inc., 2006), <http://www.atlasair.com/holdings/press/press2.asp?Pressid=363> (accessed February 2007); “747 Family: Technical Specifications – 747 Classics,” The Boeing Company, http://www.boeing.com/commercial/747family/pf/pf_classics.html (accessed February 2007).

¹⁰⁵ Todd A. Dyer, Captain, “Leasing Wide-Body Aircraft,” in *Today’s Logistics: Selected Readings and Analysis*, ed. James C. Rainey, Beth F. Scott and Gail Waller (Gunter Annex, Maxwell AFB, AL: Air Force Logistics Management Agency, 2001), 26, http://www.aflma.hq.af.mil/lgj/todays_logistics.pdf (accessed February 2007); “Commercial Airplanes: DC-10 Technical Specifications,” The Boeing Company, <http://www.boeing.com/commercial/dc-10/tech.html> (accessed February 2007); “KC-10 Extender,” U.S. Air Force, <http://www.af.mil/factsheets/factsheet.asp?id=109> (accessed February 2007).

¹⁰⁶ InterVISTAS Consulting Inc., *The Economics of Cargo Co-Terminalization*. Vancouver, Canada: InterVISTAS Consulting Inc., <http://www.cacairports.ca/news2/EconomicofCo-terminalization30Jun2005.pdf> (accessed February 2007); “Airbus A300-600,” CivilAviation.eu, <http://www.civilaviation.eu/Airbus/A300-600.htm> (accessed February 2007).

¹⁰⁷ Dyer, “Leasing Wide-Body Aircraft,” 26; “Cargo Aircraft Facts: MD11,” Air Charter Service Plc, <http://www.aircharter.co.uk/aircraft/md11.htm> (accessed February 2007); “Commercial Airplanes: MD-11 Freighter Background,” The Boeing Company, <http://www.boeing.com/commercial/md-11family/freighter.html> (accessed February 2007); “Federal Express Orders New MD-11F,” McDonnell-Douglas Co., <http://www.boeing.com/news/releases/mdc/96-174.html> (accessed February 2007).

The table illustrates the difference between a *vec* calculated using replacement cost (RC) and one calculated using an ACMI lease. In the latter case, the block hour rate – that is, the cost per flight hour for the aircraft under the lease – is multiplied by 100 (assuming the entire 100-hour minimum is flown) and divided by the cargo capacity to obtain a more accurate measure of *vec*.

b. Commodity Demand

Commodity requirements following an incident will vary depending on several factors, including the nature of the incident, its scope and its projected duration. The following commodities list is derived from examination of a range of past disasters. It is recognized that this is not a comprehensive list; however, it includes most of the major requirements common to virtually all large-scale incidents:

- Water
- Food (MREs)
- Shelter
- Electric generators
- Medicines
- Cots
- Blankets
- Tarps
- Ice
- Baby supplies
- Clothing
- Building supplies (plywood, nails, tools, etc.)
- Fuel oil
- Equipment (loaders, forklifts, medical equipment, etc.)
- Other commodities (batteries, lights, communications equipment, etc.)

Expected commodities requirements for the hypothetical scenarios are calculated for a 72-hour window forward from the initial time the incident has occurred. Table 2 lists the commodities requirements per survivor.

Item	Quantity /day /survivor	Survivors served	Notional dimensions (ft ³)			Volume (ft ³)	Total requirement/survivor (ft ³)
			L	W	H		
Water (drinking)	1 gallon	1	1.0	1.0	1.0	1.0	3.000
Water (non-potable)	1 gallon	1	1.0	1.0	1.0	1.0	3.000
Meals (MREs)	3 meals	1	1.0	1.0	1.5	1.5	4.500
Portable shelter	1 shelter	4	6.0	2.0	1.5	4.5	4.500
Basic medical kit	1 kit	3	1.0	1.0	1.0	0.3	0.333
Cot	1 cot	2	3.0	2.0	1.0	3.0	3.000
Blanket	1 blanket	1	2.0	2.0	0.5	2.0	2.000
Tarp	1 tarp	3	3.0	3.0	1.0	3.0	3.000
Ice	1 gallon	10	1.0	1.0	1.0	0.1	0.300
Baby supplies	1 box	5	1.0	1.0	1.0	0.2	0.600
Generator	1 generator	500	8.0	8.0	6.0	0.8	0.768
Clothing	1 bag	1	2.0	2.0	1.0	4.0	4.000
Plywood	2 sheets	3	4.0	8.0	0.1	1.3	4.000
Nails	1 box	3	1.0	1.0	1.0	0.3	1.000

Table 2. Commodities Calculations Summary

Different commodities will be required for the hurricane and WMD cases. Survivors of a nuclear detonation can be expected to need water, food, shelter, medical supplies, baby supplies, cots and blankets. They should not need generators, as the city's electrical grid should be able to withstand the explosive effects of the blast. Likewise, since the destructive effects of a one-kiloton blast on structures would be limited to a fairly small area, building supplies would not be in great demand. By contrast, hurricane survivors will need nearly all of the listed commodities. Hurricane scenario 1 (ω_1) assumes massive flooding in large parts of D.C. Therefore, there are many more displaced survivors, and the commodities requirements include clothing. Hurricane scenario 2 (ω_2) assumes no flooding, therefore the number of displaced persons is significantly less, and clothing is not included in the commodities calculation.

Summing the commodities requirements calculated from Table 2 results in the totals for each scenario, shown in Table 3.

HURRICANE CASE	
ω_1 - water, food, shelter, medical, cot, blanket, baby supplies	20.93 ft³
ω_2 - water, food, shelter, medical, cot, blanket, baby supplies	20.93 ft³

WMD CASE	
ω_1 - water, food, shelter, medical, cot, blanket, tarp, baby supplies, generator, clothing, plywood, nails	33.70 ft³
ω_2 - water, food, shelter, medical, cot, blanket, tarp, baby supplies, generator, plywood, nails	29.70 ft³

Table 3. Per Survivor Commodities Requirements, by Case and Scenario

c. Affected Areas

The POM defines affected areas (AAs) as “areas hit by the disaster.”¹⁰⁸ The model also uses data about each affected area, such as the commodities required, the available ramp space, and the area’s accessibility by the various TMs. In this context, “ramp space” encompasses more than just aircraft parking and taxi areas at airports. The term includes any large flat, open area suitable for parking and offloading vehicles, helicopters and VSTOL aircraft.

For the two notional test cases in Washington, D.C., four AAs are selected. Table 4 summarizes the AAs.

Affected Area	Name	Domains supported
a_1	RFK Stadium parking lot	Land
a_2	Reagan National Airport	Air, Land
a_3	Washington-Dulles IAP	Air, Land
a_4	National Mall	Land

Table 4. Affected Areas (AAs)

The four areas represent a mix of domains, locations, and ramp capacity. For simplicity’s sake, the maritime domain is not modeled. The map at Figure 5 depicts AA locations.

¹⁰⁸ Tean, *Optimized Positioning of Pre-Disaster Relief Force and Assets*, 5.

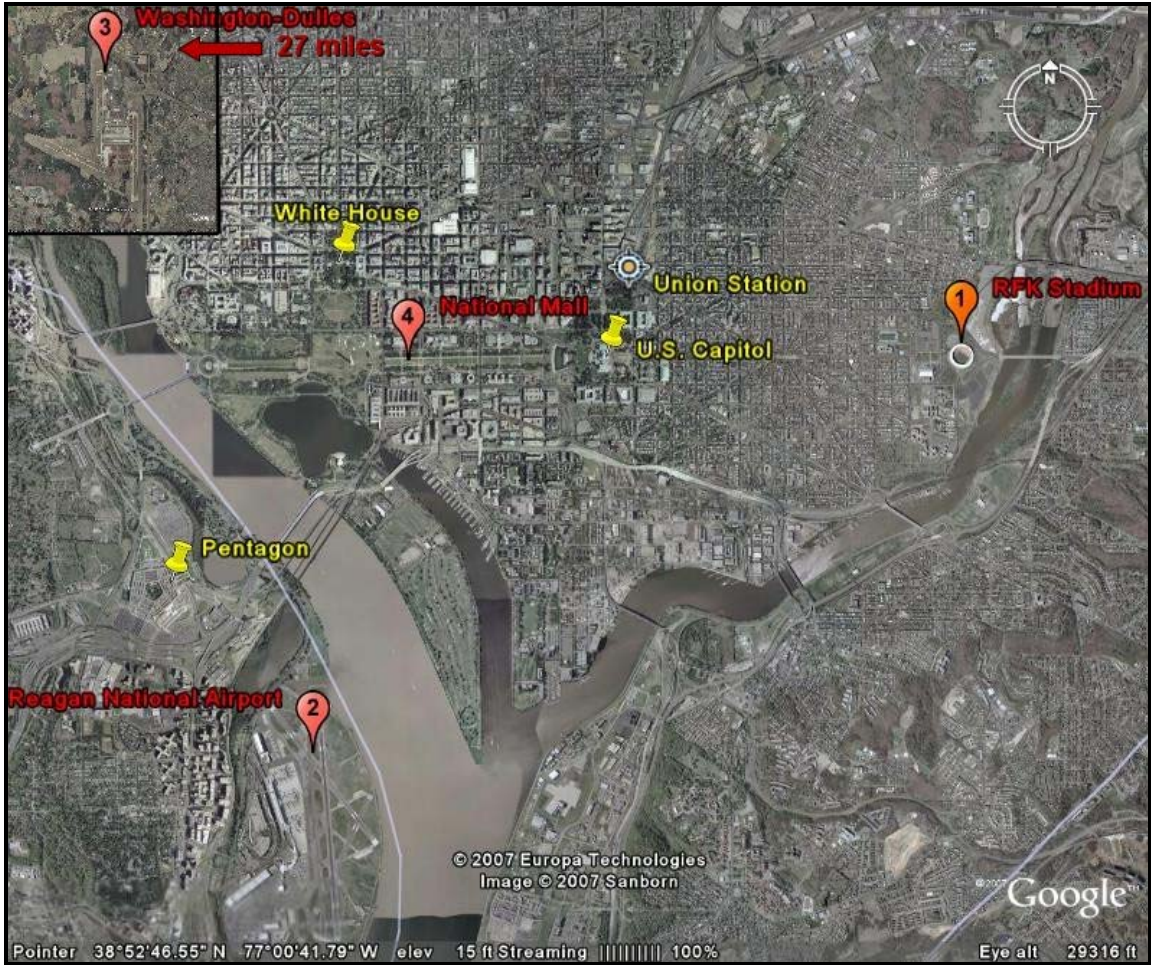


Figure 5. Washington, D.C. Showing Affected Areas¹⁰⁹

By locating the AAs at different points throughout the city, relief workers are better able to distribute commodities to displaced survivors. In a true disaster, many more distribution points would be utilized. However, four larger AAs are sufficient to demonstrate the general validity of the POM for a realistic scenario.

Ramp space for each of the AAs is calculated differently, due to the different type and fidelity of data available for each location. Ramp space at RFK Stadium is estimated from the published capacity of the parking lot for 10,000 cars and

¹⁰⁹ After Europa Technologies, “Google Earth,” <http://earth.google.com/> (accessed March 2007).

300 buses.¹¹⁰ It is assumed that the space between parking spaces, such as access lanes, added an additional 30% to the total square footage. It is estimated that the parking lot could be expanded by 50% over its current size.

Of the total acreage reserved to Reagan National Airport (a_2), 760 acres are above water.¹¹¹ It is assumed that 40% of that land is ramp space. Of that, it is further assumed that only 40% would be usable for commodity staging in a disaster, because of competing uses and inefficiencies. Because of its location, surrounded on all sides by the Potomac River and developed commercial property, Reagan National has very little land within which to build additional ramp space. Accordingly, the model assumes a maximum expansion of 20% over the current usable space.

By contrast, Washington-Dulles International Airport (a_3) is located on a broad, flat plain roughly 25 miles northwest of the city. Its present size is 11,830 acres, of which 5,000 acres is reserved for aircraft operations.¹¹² As with Reagan National, it is assumed that 40% of that 5,000 acres, or 2,000 acres, comprises ramp space. Likewise, it is also assumed that 40% of that 2,000 acres would be usable for commodity staging. Unlike Reagan National, Washington-Dulles has much more undeveloped land around it. Therefore, it is assumed that the airport could expand its ramp space by an additional 70% of the total acreage currently dedicated to aircraft operations, or 3,500 acres.

The National Mall (including West Potomac Park and Constitution Gardens) is one of the largest areas of contiguous open land in the District of Columbia. It is also centrally located to several major government buildings and commercial areas. It runs in an east-west orientation from the Capitol Building to the east to the Lincoln Memorial at its western edge, with the Washington Monument dividing the area slightly west of center. From the Grant Statue, just west of the Capitol, to the Lincoln Memorial

¹¹⁰ “RFK Stadium,” MLB Advanced Media, <http://washingtonnationals.mlb.com/NASApp/mlb/was/ballpark/history.jsp> (accessed February 2007).

¹¹¹ “Facts about Ronald Reagan Washington National Airport,” Metropolitan Washington Airports Authority, http://www.metwashairports.com/reagan/about_reagan_national/facts_3 (accessed February 2007).

¹¹² “Facts about Washington-Dulles International Airport,” Metropolitan Washington Airports Authority, http://www.metwashairports.com/dulles/about_dulles_international_2/facts_2 (accessed February 2007).

is 309 acres.¹¹³ Not all of this area is available to land and air traffic, owing to trees, monuments, and other areas such as the Lincoln Memorial Reflecting Pool. Discounting for unusable areas, it is estimated that 70% of the 309 acres would be available for “ramp space.” The area surrounding the National Mall is heavily developed. Therefore, the model assumes that no expansion space is available.

Initially, ramp space is calculated in two dimensions, using the methods and estimates discussed *supra*. Because the POM’s standard unit of measurement is the cubic foot, it is necessary to convert the calculated area numbers to volume figures. This is done by assuming that the entire usable area (again, accounting for transit corridors and turnabout areas) could be filled with LD3 container units, unstacked. The LD3 is a Unit Load Device, or ULD, of the sort used in the cargo industry. Its dimensions are 70” wide, 60.4” deep and 64” high. It can be employed in all of the aircraft used in the model.¹¹⁴ It is used as the prototypical cargo container for this reason, and because of its ubiquitous nature in the air cargo industry. Accordingly, each ramp space linear dimension is converted to a volume figure by multiplying it by 5.33 feet, the height of a standard LD3 container.

The cost of ramp space expansion is derived from information graciously provided by Mr. Bob Beesley of the Memphis-Shelby County Airport Authority. Memphis International Airport just added a new cargo ramp at a cost of about \$14 per square foot. That work, on a basically prepared site, included modest fine grading, ramp lighting and spill control measures.¹¹⁵ For Dulles and Reagan airports, ramp expansion is assumed to cost an equivalent \$14/sq. ft. For the RFK Stadium parking lot, the cost is discounted by 20%, to \$11.20/sq. ft., because of the absence of ramp lighting and spill control measures.

¹¹³ “National Mall,” Wikimedia Foundation, Inc., http://en.wikipedia.org/wiki/National_Mall (accessed February 2007).

¹¹⁴ “Unit Load Device,” Wikimedia Foundation, Inc., http://en.wikipedia.org/wiki/Unit_Load_Device (accessed 10 February 2007).

¹¹⁵ Robert Beesley (Director of Development, Memphis-Shelby County Airport Authority), e-mail message to author, 14 February 2007.

Table 5 summarizes the affected area data.

Affected Area	Name	Initial Ramp Capacity (ft ³ x 1000)	Max Expansion (ft ³ x 1000)	Expansion Cost (\$/ft ³ x 1000)
a_1	RFK Stadium parking lot	3,346	1,673	11,200
a_2	Reagan National Airport	28,250	14,125	14,000
a_3	Washington-Dulles IAP	185,656	813,120	14,000
a_4	National Mall	43,096	0	11,200

Table 5. Affected Area Data Summary

For all scenarios in both test cases, this information remains unchanged.

d. Relief Locations

Relief locations (RLs) in the POM are hubs to receive commodities and workers and process them for further deployment to the disaster site. As Captain Tean’s thesis indicates, RLs represent places where relief units and assets are located, usually away from the AAs.¹¹⁶ Within DOD, these sites are often referred to as RSOI (Reception, Staging, Onward movement, and Integration) locations, or JRSOI locations if operating in a joint environment. Borrowing the military’s formal description of the process, a JRSOI location may be defined as “[locations] required to transition arriving personnel, equipment, and materiel into [relief packages] capable of meeting operational requirements.”¹¹⁷

Four relief locations are modeled. The locations are described in Table 6.

Relief Location	Name	Domains supported	Operations
l_1	Memphis TN Int’l Airport	Air, Land	FedEx national air/land hub
l_2	Louisville KY Int’l Airport	Air, Land	UPS national air/land hub
l_3	Indianapolis IN Int’l Airport	Air, Land	U.S. Postal Service national airborne freight hub
l_4	Philadelphia PA Int’l Airport	Air, Land	UPS regional air/land hub

Table 6. Relief Locations (RLs)

¹¹⁶ Tean, *Optimized Positioning of Pre-Disaster Relief Force and Assets*, 5.

¹¹⁷ U.S. Department of Defense, Joint Chiefs of Staff, *Joint Publication 1-02, Department of Defense Dictionary of Military and Associated Terms* (Washington, D.C.: U.S. Department of Defense).

These four locations represent the largest air and land commercial cargo facilities in the same general region as Washington, D.C. The Federal Express cargo facility at Memphis International Airport is the world's largest and busiest domestic freight facility, in terms of total cargo processed annually. Louisville is third, after Los Angeles International Airport. Indianapolis is seventh, and Philadelphia thirteenth.¹¹⁸ However, when one considers strictly domestic cargo carried, many of the airports ranked higher than Indianapolis and Philadelphia in total "landed weight" – Los Angeles, Miami, New York Kennedy, and Chicago O'Hare, for example – lag both cities. In addition, all four airports have large ground freight processing facilities. For example, the FedEx "Superhub" at Memphis International Airport routinely processes a half-million packages an hour, while the UPS Worldport is capable of sorting 304,000 packages per hour.¹¹⁹

Analogous to the AAs, the POM uses commodity capacity, maximum expansion capacity and variable expansion cost in its relief location calculations. Unlike the affected areas, however, RL capacities are for warehouse space alone, not ramp space. In this regard, the model will tend to undershoot the actual space available for uploading, offloading and transferring cargo, but any error is to the conservative side. Additionally, this thesis assumes that only 20% of current warehouse capacity would be available for disaster relief. This is slightly more than the CRAF required minimum of 15%, and represents a reasonable upper limit on the amount of business the commercial cargo companies could divert to support disaster relief efforts on short notice.

Like the AAs, data on RL warehouse space is inconsistent, requiring discrete calculations for each. The UPS Worldport cargo facility at Louisville International Airport contains 4,000,000 square feet. To obtain the present commodity

¹¹⁸ "2005 Cargo Rankings: United States Airports," Miami International Airport, http://miami-airport.com/html/cargo_rankings_.html (accessed February 2007); Jane Roberts, "Memphis International Airport Winging its Way to Success Despite some Turbulence," *Memphis Commercial Appeal* (31 December 2006), under "News/Business," http://www.commercialappeal.com/mca/business/article/0,1426,MCA_440_5247559,00.html.

¹¹⁹ Associated Press, "FedEx Hub Traffics in Holiday Chaos," *MSNBC*, <http://www.msnbc.msn.com/id/16230038>; "Fact Sheets: Quick Facts -- UPS Worldport," United Parcel Service of America, Inc., <http://www.pressroom.ups.com/mediakits/factsheet/0,2305,927,00.html?mkname=uspairlines> (accessed 18 February 2007).

capacity, square footage is converted to cubic feet by assuming the equivalent of three LD3 container units could be stacked within the interior of the warehouse, to a height of 16 feet. Maximum expansion is set at 1,100,000 square feet or 17.6 million cubic feet, based on UPS' current expansion plans for the facility.¹²⁰

For Memphis International, warehouse space is first estimated from the annual cargo throughput figures. Memphis moves twice the annual cargo of Louisville International, therefore it is assumed to have twice the warehouse space. This is confirmed by approximating the FedEx Superhub's warehouse volume to be 60% of its total acreage, e.g. 294 acres. Memphis International Airport is not constrained by geographic features or dense urban growth. In fact, the airport recently expanded its ramp space by over 650,000 square feet.¹²¹ Accordingly, a moderate expansion factor of 30% is assumed.

The UPS warehouse at Indianapolis International Airport is 2,000,000 square feet in size.¹²² Again assuming the warehouse could be stacked three deep with LD3 containers, this converted to 32 million cubic feet of initial capacity, of which 20%, or 9.6 million cubic feet, is assumed to be available for disaster relief.

Finally, Philadelphia's warehouse space is estimated by noting that its annual landed cargo weight is approximately 30% that of Louisville. With little data available, it is somewhat arbitrarily assumed that Philadelphia could expand its warehouse capacity by 30%.

The POM uses variable expansion cost to determine whether some of the allocated budget amount should be spent to expand warehouse capacity. Since this

¹²⁰ "Louisville International Airport: Fast Facts," Louisville Regional Airport Authority, <http://flylouisville.com/about/fastfacts.asp> (accessed February 2007); Adam Bruns, "Overnight Success," *SITE Selection* (September 2006), under "Logistics," <http://www.siteselection.com/features/2006/sep/logistics>.

¹²¹ Robert Beesley (Director of Development, Memphis-Shelby County Airport Authority), e-mail message to author, 24 February 2007.

¹²² Chris O'Malley, "Air Cargo Facility on Tap? Airport Studying Whether a New Hub could be Beacon for Global Carrier System," *Indianapolis Business Journal* (2007), <http://www.indianaeconomicdigest.net/main.asp?SectionID=31&SubSectionID=66&ArticleID=32100> (accessed February 2007).

budget represents federal funds, it is unrealistic to expect that the federal government would pay the entire cost for expanding a commercial cargo facility. Therefore, the calculated costs for constructing additional warehouse space were reduced by 50%. This represents a notional arrangement in which the federal government agrees to pay 50% of the cost of expansion, in exchange for which the cargo company agrees to reserve the expanded space for government operations, including disaster relief.

The cost for expanding Worldport is assumed to be the same as the cost of initial construction, or \$300 per square foot. Using the notional arrangement construct, that amount is reduced by 50%, to a final figure of \$150 per square foot. This amount is used for variable expansion cost for Louisville, Memphis and Philadelphia. The UPS facility at Indianapolis International Airport has published plans to expand its warehouse capacity by 600,000. The \$214 million estimated construction cost equates to \$357 per cubic foot, or \$178.50 per cubic foot when reduced by 50%.

The POM assumes that health care personnel will be picked up at RLs and transported to AAs to work in those affected areas. Therefore, for each RL the model also utilizes information on initial capacity, maximum expansion, and variable expansion cost for health care personnel. In the absence of better data sources, this thesis incorporated the data used by Captain Tean in his earlier research.¹²³

Table 7 details the four relief locations.

Relief Location	Name	Initial Warehouse Capacity (ft³ x 1000)	Max Expansion (ft³ x 1000)	Expansion Cost (\$/ft³ x 1000)
l_1	Memphis TN IAP	24,589	36,883	150,000
l_2	Louisville KY IAP	12,800	17,600	150,000
l_3	Indianapolis IN IAP	6,400	9,600	178,500
l_4	Philadelphia PA IAP	3,840	5,760	150,000

Table 7. Relief Location Data Summary

¹²³ See generally Tean, *Optimized Positioning of Pre-Disaster Relief Force and Assets*, 21-22.

e.. Other Data

The POM uses three other data elements: budget, survivor penalty, and number of survivors per health care worker. As will be discussed *infra*, the budget is varied in increments to observe its effect on the model's outputs. The other two parameters, survivor penalty and number of survivors per health care worker, remain constant across test cases and scenarios. The former represents a penalty function of ten survivors per thousand cubic feet of undelivered commodities. It is introduced in the POM to reflect an increase in the number of deaths if the survivors' commodity requirements are not met.¹²⁴ The latter is set in the original research at five survivors per health care worker. That number has been carried over to this thesis without change.

The POM also requires transit times for all TMs from RLs to AAs. Air mileage from each RL to each AA is obtained through an Internet-based air mileage calculator.¹²⁵ Driving mileage for ground vehicles is obtained from Mapquest.¹²⁶ Enroute time is then calculated for all possible routes. The results are summarized in Appendix B.

2. Assumptions and Limitations

While every effort was made to use *bona fide* data from reliable sources, inevitably compromises had to be made. Several assumptions were made in calculating data used in the model. Some of these are discussed in Captain Tean's thesis.¹²⁷ Others are discussed in subsection 1 above. Some additional assumptions include:

- Security in the affected areas is sufficient to permit TMs to transit in and out safely and without impedance
- All displaced persons need commodities, in equal amounts
- Commodity requirements are aggregated for the duration of the 72-hour period of inquiry

¹²⁴ See generally Tean, *Optimized Positioning of Pre-Disaster Relief Force and Assets*, 6.

¹²⁵ "Air Mile Calculator," Airtimetable.com, http://www.airtimetable.com/Air_mile_calculator.htm (accessed February 2007).

¹²⁶ "MapQuest," MapQuest, Inc., <http://www.mapquest.com> (accessed February 2007).

¹²⁷ See generally Tean, *Optimized Positioning of Pre-Disaster Relief Force and Assets*.

- All commodities delivered to AAs are distributed to displaced persons
- Displaced persons do not move from one AA to another
- All survivors have equal evacuation priority
- Each health care worker is able to care for five survivors, regardless of profession (nurse, doctor, pharmacist, etc.)
- Special mission aircraft (CH-53S, MV-22S) are only configured for medical evacuation
- General mission aircraft can deliver only commodities or relief workers
- All TMs are immediately available for use
- Any required maintenance or refueling on TMs is performed in the hours the TM is not available (see Appendix A)
- All available and usable cargo space in the TMs is used on each trip
- There are enough drivers and aircrew members for all TMs at all times during TM hours of availability
- TMs proceed by the most direct route to and from AAs and RLs
- Weather patterns (winds, precipitation, temperature, cloud cover, water levels) remain constant throughout the 72-hour period

The model also has several limitations, some structural, and others the result of the assumptions articulated above. These limitations include the following:

- The probabilities assigned to the two scenarios bound the possible POM solutions. It is left to further research to determine whether altering the probabilities significantly changes the model results.
- The model can only indirectly account for changes in weather, by altering enroute times or rendering a particular route infeasible.
- Self-help by persons within the affected areas is not modeled.
- The contributions of non-governmental organizations (NGOs), community groups, and ad hoc aid groups are not considered.
- The generic category of “workers” is not further categorized, for instance by skills, profession, or mission assignment.
- Requirements for support equipment, such as forklifts, pallets, portable toilets, and communications equipment, are not included.
- Legal restrictions are ignored, for instance professional licensure and accreditation requirements for health care workers, zoning restrictions, and environmental impact study requirements.

- Social effects are not modeled. These include inaccurate media reporting, large non-native English speaking populations, and criminal activity. All of these may dramatically alter factors such as the accessibility of AAs, survivor requirements, and the number of survivors needing rescue.
- Certain effects are beyond the POM's current capabilities to model. Examples include degraded communications, ambiguous or contradictory command and control, or multiple, parallel logistics processes.

3. Testing the Hypothesis

Admittedly, the POM paints with a fairly broad brush. The purpose of this thesis, and of the POM itself, is not to model with precision the optimum logistics response to given test cases and scenarios. Rather, the objective is to assess the validity of the POM as a strategic decision-making tool. It is hypothesized that the outputs of the POM, generated under different sets of conditions, will provide strategic guidance to senior policymakers. In turn, the strategic choices made with reference to the model's results will reduce the resource gap between the exhaustion of state and local capabilities and the arrival of sufficient federal resources to meet commodity requirements. Two notional cases are used to test the hypothesis.

C. TEST CASES

The two test cases developed to evaluate the validity of the POM share Washington, D.C. as the common situs. The cases represent the spectrum of advanced notice: a sudden terrorist attack with no warning, and a hurricane that has moved up the East Coast over a period of days before striking the nation's capital. In the terrorist attack case, the model examines the response to a one-kiloton (1 kT) nuclear detonation near Union Station in downtown Washington, D.C. In the latter case, disaster relief efforts commence after a Category IV hurricane has passed directly over the city. In addition to simulating different preparation periods, the test cases also exemplify real-world threats facing the National Capital Region.

Both test cases are further subdivided into two scenarios. The first scenario, denominated ω_1 for each test case, assumes a "worse case" condition, while the second scenario (ω_2) describes a "better case." To account for the relative likelihood of each scenario, ω_1 is assigned a probability of 0.25, while the probability of the less serious

scenario (ω_2) occurring is fixed at 0.75. The assignment of probabilities to the two scenarios narrows the model's focus and imposes boundaries on possible solutions. While for simplicity's sake this thesis examines only two scenarios per test case, the POM can be run with multiple scenarios simultaneously, each with a discrete probability assigned. This aspect of the model is particularly valuable when assessing data trends, and evaluating the sensitivity of the outputs to changes in scenario inputs.

1. One-Kiloton Nuclear Detonation

The first notional case is a small nuclear device exploding above ground near Union Station. The two scenarios are identical except for the wind direction. In Scenario 1 (ω_1), at the time of the explosion winds are from the northeast at 15 knots. Scenario 2 (ω_2) assumes winds from the west, also at 15 knots. The different wind directions force the POM to adjust for the unavailability of different commodity drop-off locations. In Scenario 1, the National Mall is unavailable because of the potential for fallout. For the same reason, RFK Stadium's parking lot is unavailable in Scenario 2.

The map in Figure 6 was generated by the Defense Threat Reduction Agency (DTRA). It displays the projected plume of a 1 kT explosion near Union Station, given prevailing wind patterns from the southwest. Wind arrows for Scenario 1 (northeast winds at 15 kts) and Scenario 2 (west winds at 15 kts) are superimposed to permit visualization of the plumes for those respective conditions.

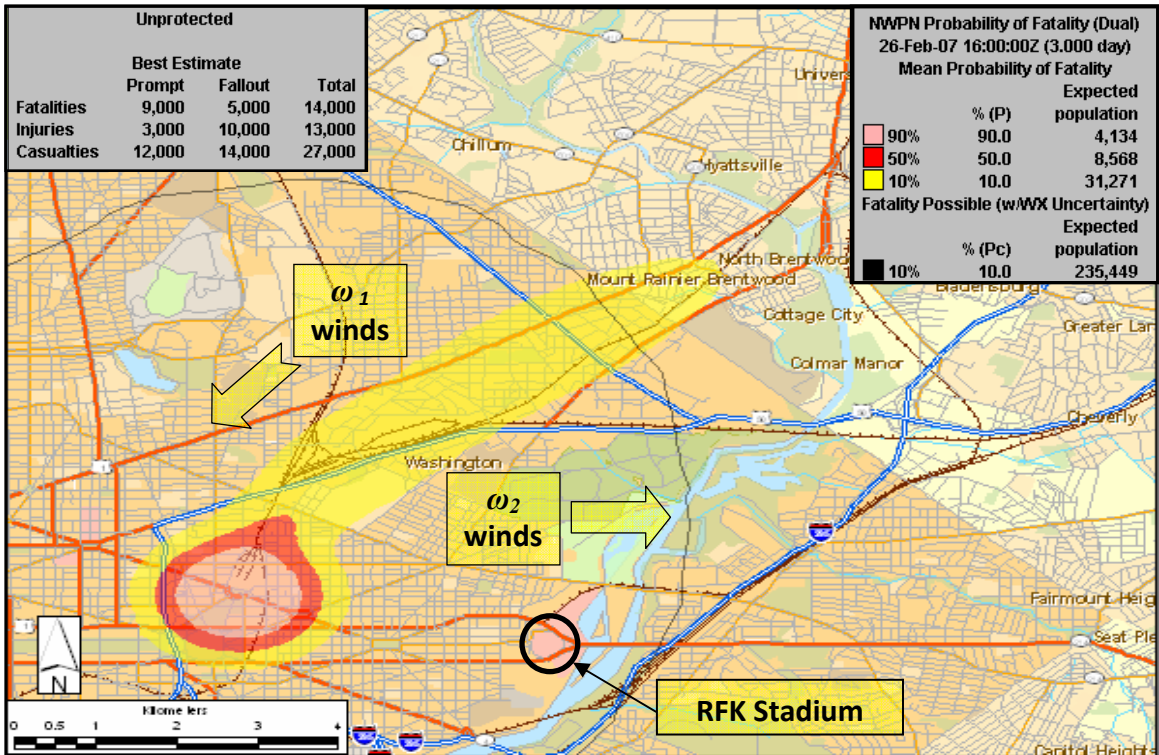


Figure 6. Plume Analysis of 1 kT Explosion at Union Station¹²⁸

By far the greatest impact of the nuclear detonation would be fallout. As depicted in Figure 7, damage to structures from the blast effects would be limited to an area of less than a quarter-mile radius from the epicenter of the blast. Therefore, most casualties will come from radiation exposure.

¹²⁸ After Defense Threat Reduction Agency, *1kT Detonation at Union Station* (Washington, D.C.: Defense Threat Reduction Agency, 27 February 2007), PowerPoint slides.

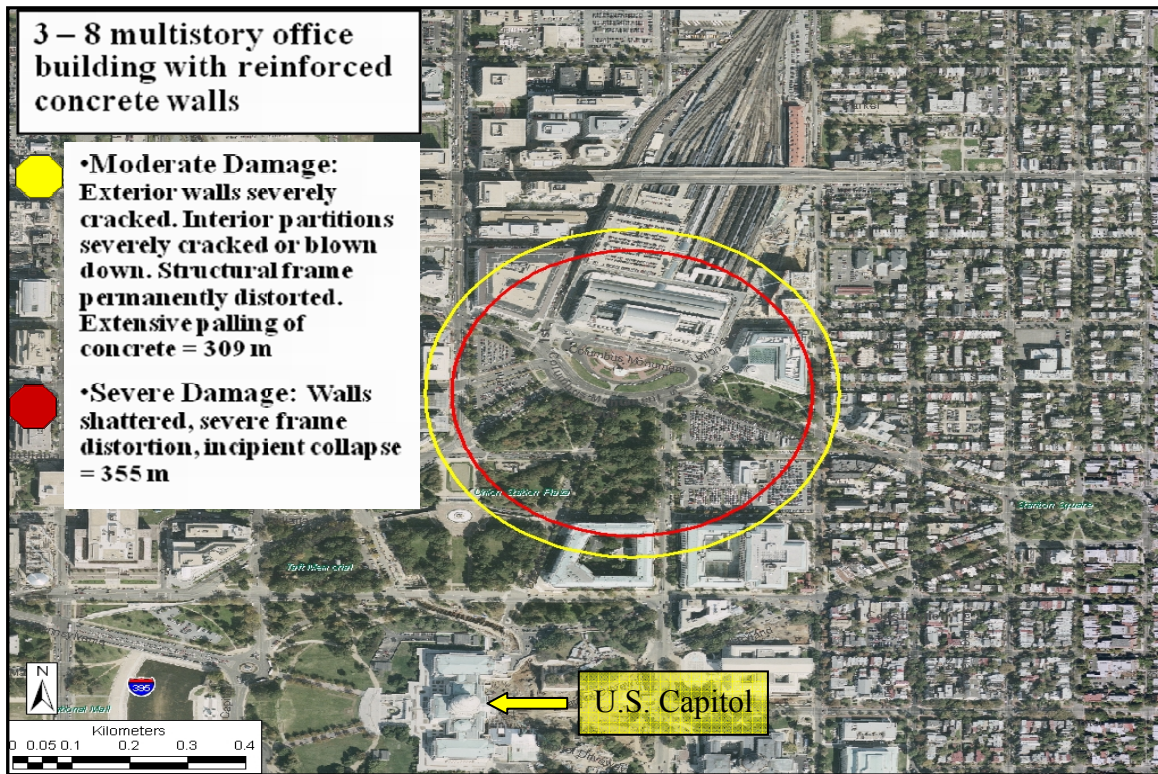


Figure 7. Union Station WMD -- Structural Damage from Air Blast Overpressure¹²⁹

It is assumed that the detonation takes place on a work day, during working hours. In the first scenario, the fallout is blown toward the densely populated area of multi-story government and commercial buildings west and south of Union Station. Therefore, total persons in need of medical care (“Potential Survivors” in the POM) number 25,000 for Scenario 1, higher than the 15,000 person estimate for Scenario 2. The distribution of potential survivors is effected according to the wind pattern. For the northeast winds of Scenario 1, a greater proportion of survivors are evacuated to RFK Stadium, away from the plume direction. For the west winds of Scenario 2, the greatest numbers of survivors congregate at the National Mall, also away from the plume. The two airports, Reagan National (a_2) and Dulles (a_3), receive fewer people in need of medical care, in part because of their distance from the incident site.

¹²⁹ After Defense Threat Reduction Agency, *1kT Detonation at Union Station* (Washington, D.C.: Defense Threat Reduction Agency, 27 February 2007), PowerPoint slides.

Total commodity requirements are estimated by multiplying the number of displaced persons by the amount of commodities needed per person, from Tables 2 and 3 *supra*. In turn, requirements are allocated to affected areas in proportion to the number of survivors at each AA.

The potential survivors and commodity requirements for the WMD test case are summarized in Table 8.

Affected Area	Potential Survivors		Commodity Requirements (ft ³ x 1000)	
	NE Winds (ω_1)	W Winds (ω_2)	NE Winds (ω_1)	W Winds (ω_2)
a_1	15,000	0	753	0
a_2	2,500	3,500	126	195
a_3	7,500	2,500	377	140
a_4	0	9,000	0	502

Table 8. WMD Detonation – Potential Survivors and Commodity Requirements

2. Category 4 Hurricane

The hypothetical case of a Category IV hurricane striking a major metropolitan area corresponds to Planning Scenario 10 (Natural Disaster – Major Hurricane) of the fifteen National Planning Scenarios.¹³⁰ Although Planning Scenario 10 assumes a Category V hurricane, the casualty and flooding estimates are comparable between Planning Scenario 10 and the test case used here. In addition, it is likely that a hurricane making landfall southeast of Washington, D.C. would lose some of its strength before reaching the city, as depicted in the DTRA wind forecast model shown in Figure 8.

¹³⁰ U.S. Department of Homeland Security, *National Planning Scenarios: Created for Use in National, Federal, State, and Local Homeland Security Preparedness Activities* (Washington, D.C.: U.S. Department of Homeland Security, 2004).

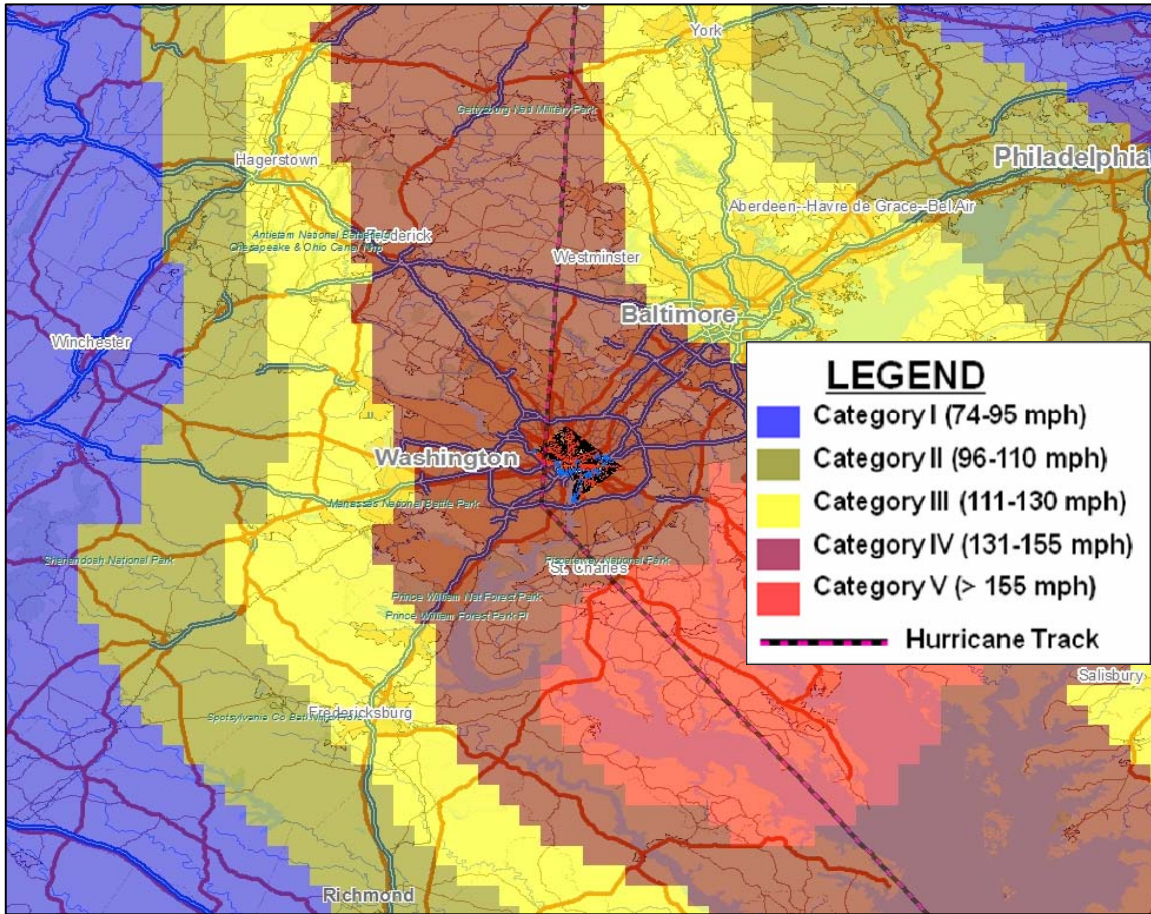


Figure 8. Category IV Hurricane -- Wind Speed Model¹³¹

Compared to the nuclear detonation case, a major hurricane would leave widespread damage in its wake. Depending on the size of the storm surge, critical infrastructure such as power stations, bridges, roads and airports could be adversely affected. The two hurricane scenarios simulate these different degrees of impact. Scenario 1 (ω_1) posits widespread flooding, in particular in the south and southeast parts of the city. Figure 9 maps the areas likely to be impacted by light to moderate flooding.

¹³¹ Defense Threat Reduction Agency, *Impact of a Category IV Hurricane on Washington, D.C.* (Washington, D.C.: Defense Threat Reduction Agency, 27 February 2007), PowerPoint slides.

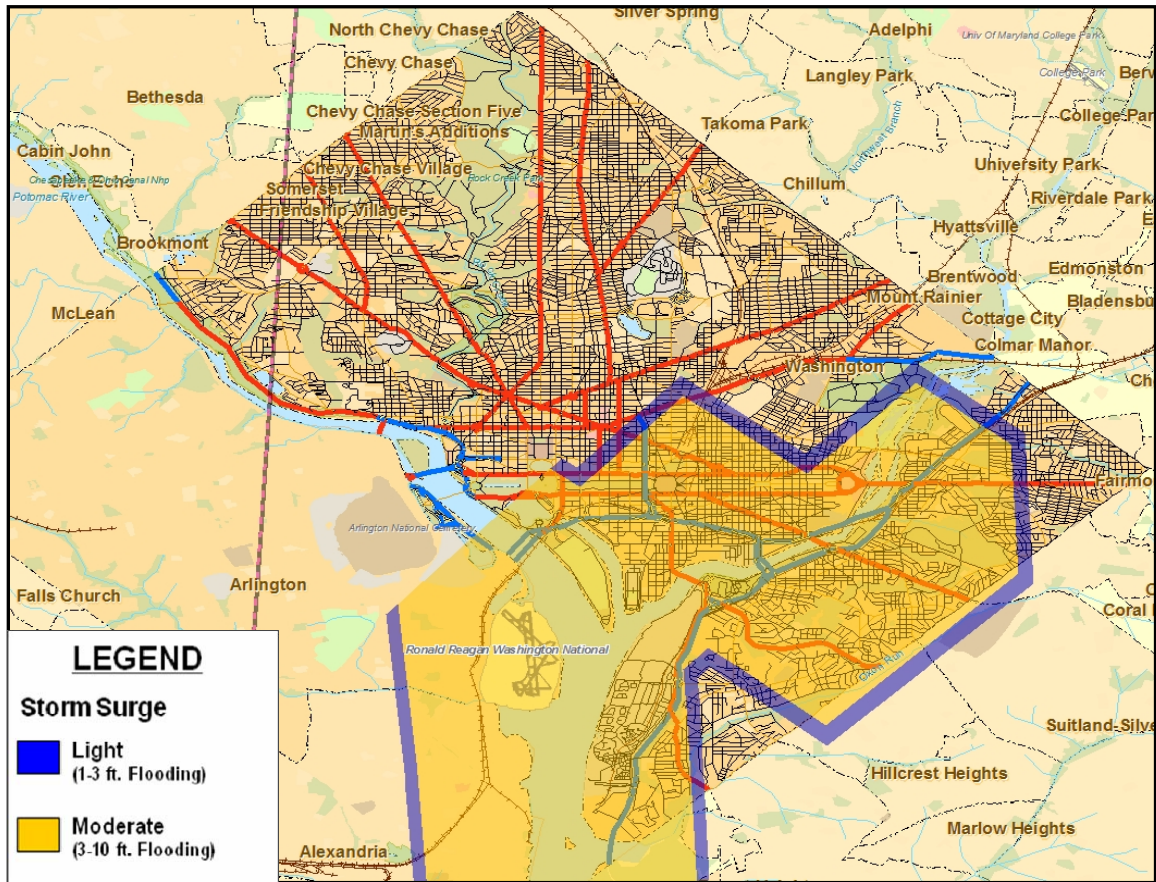


Figure 9. Category IV Hurricane -- Storm Surge Forecast¹³²

Based on Figure 9, Scenario 1 assumes that Reagan National is inaccessible to other land and air TMs. It further assumes that the bridge crossings to the city are degraded, resulting in increased travel times for land TMs. Because the massive flooding will displace many more residents from their homes, the number of displaced persons in Scenario 1 is 180,000, vice 35,000 for Scenario 2. Likewise, the flooding can be expected to increase the number of potential survivors. The scenarios reflect this – total potential survivors for Scenario 1 is 25,000, while the total for Scenario 2 is 7,000.

¹³² Defense Threat Reduction Agency, *Impact of a Category IV Hurricane on Washington, D.C.* (Washington, D.C.: Defense Threat Reduction Agency, 27 February 2007), PowerPoint slides.

Like the WMD test case, total commodity requirements are derived by multiplying the total number of displaced persons by the amount of commodities needed per person, from Tables 2 and 3 *supra*. Requirements for each AA are then allocated in proportion to the number of survivors at each AA.

Table 9 summarizes the data for the hurricane test case.

Affected Area	Potential Survivors		Commodity Requirements (ft ³ x 1000)	
	Mass Flooding (ω_1)	No Flooding (ω_2)	Mass Flooding (ω_1)	No Flooding (ω_2)
a_1	10,000	3,500	2,426	520
a_2	0	800	0	119
a_3	2,500	0	607	0
a_4	12,500	2,700	3,033	401

Table 9. Hurricane – Potential Survivors and Commodity Requirements

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V. FINDINGS

Notwithstanding the inherent limitations on the data and the model discussed in Chapter IV, the POM fulfills its promise as a strategic tool. Its outputs illuminate trends and relationships that planners and policymakers can use to best allocate scarce public funds to enhance readiness and improve incident response. In short, the hypothesis has been proved: strategic decisions made by reference to the POM can reduce the resource gap between the exhaustion of state and local resources and the arrival of federal aid.

In general terms the POM's outputs are illuminating in a number of respects. Appendix C summarizes the potential survivors not saved, commodities not delivered, and amounts spent for the WMD test case and its two scenarios, through a range of budgets from a low of \$8 million to a maximum of \$200 million. Appendix D summarizes the results for the hurricane test case.

The first observation relates to the outputs for both "better case" scenarios, labeled ω_2 for both test cases. The outputs indicate that Washington, D.C. could adequately respond to a small (1 kT) nuclear detonation or a Category IV hurricane with no flooding with modest strategic expenditures, and without the necessity for large-scale contracted transportation support. For all ω_2 , irrespective of budget, virtually all commodities are delivered, and all (or nearly all) potential survivors are evacuated. Only rarely do actual expenditures even approach the budgeted amounts, and then only at lower budget levels – roughly \$50 million for the hurricane case, and \$25 million for the WMD case.

Even for the more problematic scenarios (ω_1 for both test cases), the combination of organic federal resources and readily available commercial transportation means typically results in a high percentage of potential survivors saved, and required commodities delivered. However, these scenarios are characterized by higher expenditures relative to the budget. For the WMD case, the model calls for essentially the entire budget to be spent for budget levels up to \$60 million. Thereafter, increasing

the budget does not decrease the number of survivors lost, which is already zero by that point. Likewise, all commodities are delivered in virtually every WMD ω_1 case, irrespective of budget.

The ω_1 mass flooding hurricane scenario causes more problems, primarily because of the loss of Reagan National Airport and the degradation of ground routes into and out of the city. One consequence of the limitations is the persistence of a core number of unrescued survivors for a wide budget range, from \$8 million through \$50 million. Only at budget amounts above \$50 million does the number of unrescued survivors eventually taper off, finally reaching zero at a \$200 million budget level. This is perhaps explained by the high cost of procuring more rescue helicopters to save the remaining survivors, in lieu of much cheaper ground transportation means that cannot be used because of flooding. If flooding is indeed the cause of the increased numbers of unsaved survivors, one would expect a more linear relationship between expenditures and survivors saved for the WMD case, where access routes are open. The POM bears this out, as shown in Figure 10.

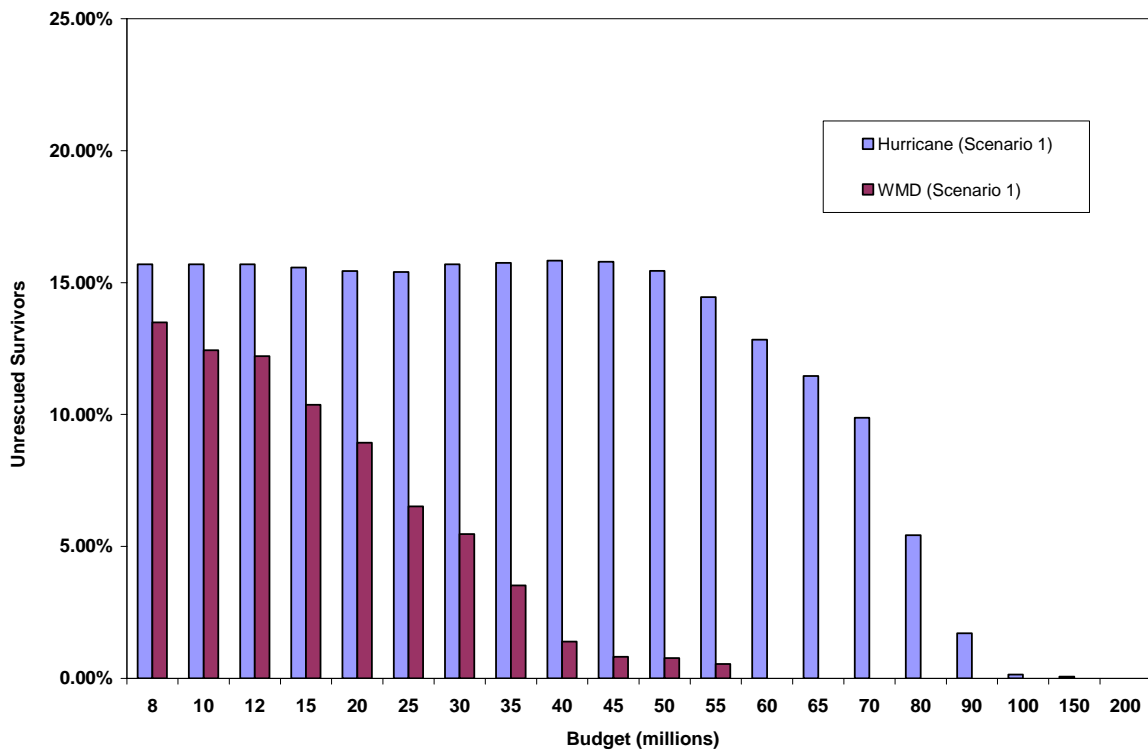


Figure 10. Budget vs. Unrescued Survivors (As Percentage of Total Survivors)

Other conclusions, less obvious from the outputs, are significant in their own right. None of the model outputs calls for ramp space expansion. This holds true despite the data reflecting some conservative assumptions regarding ramp space. For example, in calculating available ramp space at Reagan National and Dulles, only 40% of the total airport acreage is considered. Of that, only 40% is deemed available for commodity staging operations, or a combined 16% of total airport acreage. Even with this restriction, the POM does not allocate any budget amounts to ramp expansion. This may be attributed to the scale of the notional disasters. The largest scenario, hurricane Scenario 1, assumes 180,000 displaced persons. This is approximately one-third of the population of Washington, D.C., from a 2003 estimate.¹³³ Ramp expansion might be called for if the scenario assumed that two-thirds of the population is displaced.

On the other end of the supply chain, the POM suggests expansion of warehouse space at only one relief location (RL), Indianapolis International Airport, and then only during the hurricane mass flooding scenario. Common sense supports this result. In a real disaster response that includes the commercial carriers, the greatest share of air cargo traffic will pass through Memphis and Louisville, the FedEx and UPS hubs. Both of those locations have outsized cargo processing facilities with millions of square feet inside. As a concession to the economic realities of the commercial cargo business, the POM assumes that only 20% of the total warehouse capacity at the RLs will be dedicated to disaster relief. Even with that significant reduction, the model does not allocate any funds to warehouse expansion at the RLs except under the most trying scenario, and then only at Indianapolis. There is an object lesson here for government logistics planners and policymakers. Pre-arranged partnerships with the commercial cargo industry will pay huge dividends when surge transportation is needed. The major commercial freight companies have vast resources across the spectrum of transportation activities and domains, from distributed networks of warehouses to aircraft, step vans, tractor trailers, and even an armada of forklifts.

¹³³ “Washington, D.C.: Population Profile,” Thomson Gale, <http://www.city-data.com/us-cities/The-South/Washington-d-d-Population-Profile.html> (accessed 22 February 2007).

When considering transportation means, the POM expresses a clear preference for tractor-trailers. This is not surprising: they are much cheaper than air transports, carry large volumes of goods, and are ubiquitous. With closed land routes in hurricane Scenario 1, the model prefers the military transport aircraft, specifically the C-17 and the CH-53. Commercial cargo aircraft are used, but to a lesser extent. This trend endures even when the variable expansion cost for commercial cargo aircraft is cut significantly through the use of ACMI leases. The exception is the B747 outfitted to carry passengers. This is the POM's preferred method for moving large numbers of workers to the affected areas.

Arguably the finding with the most significance for strategic policymaking relates to unrescued survivors. Even at low budget levels, the percentage of potential unrescued survivors remains relatively small, typically hovering around 15%. While increasing the budget does reduce the number and percentage of unrescued survivors, the per-person rescue costs rise dramatically as the absolute number of unrescued survivors declines. This variation on the law of diminishing returns is graphically illustrated in Figure 11, which plots the change in ratio of rescued survivors to budget (i.e., dollars per rescued survivor).

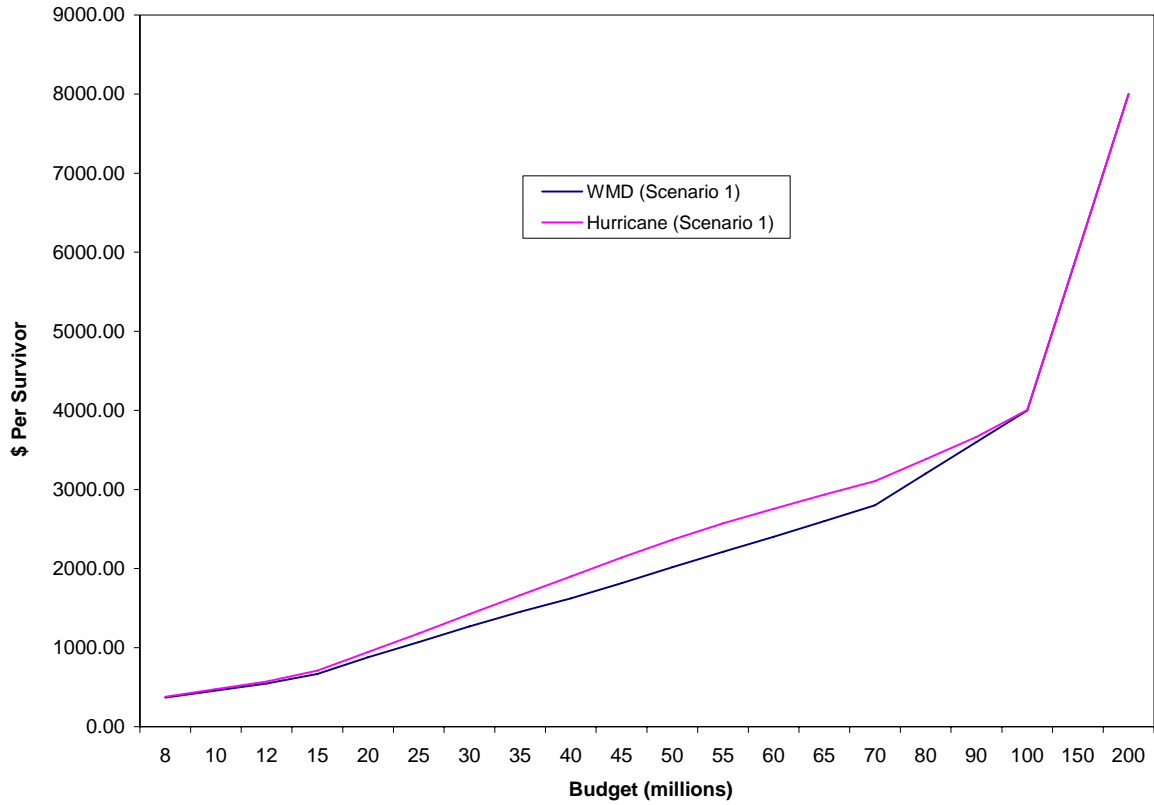


Figure 11. Expended Dollars Per Rescued Survivor

Of course, the overarching policy issue is where to set the threshold? Is there a putative ceiling on the per-person rescue cost, given the realities of federal funding streams that are limited in both time and amount? The question cannot be answered without reference to moral, ethical, legal and political considerations. Still, POM outputs provide policymakers with a baseline for evaluation, and a degree of situational awareness which has heretofore been absent.

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VI. CONCLUSIONS AND RECOMMENDATIONS

At the outset, it was shown that humanitarian logistics is a critical, but oft-slighted, element of an effective disaster relief process. Examination of the relief efforts following Hurricanes Andrew and Katrina, the Asian tsunami, and other major disasters revealed that a resource gap (“gap of pain”) frequently develops between the time when state and local resources are exhausted, and sufficient federal replacements arrive. Reducing this gap necessitates the effective balancing of four alternative approaches to managing the supply chain: pre-positioning, proactive deployment, surge transportation, and phased deployment. The optimal blend of approaches requires strategic assessment of conditions such as warehouse space, ramp space, available transportation means, and demand for commodities, workers and health care personnel. This paper hypothesized that the Pre-positioning Optimization Model (POM) could provide planners and decision makers with strategic information on the optimal placement and mix of relief assets. In turn, it has been proposed that such information could be used to reduce the gap of pain by improving the flow of workers and commodities into and out of a disaster area.

To test the hypothesis, data were gathered to support two hypothetical incidents occurring in the Washington, D.C. area: a terrorist detonation of a one-kiloton nuclear weapon near Union Station, and a Category IV hurricane passing over the city. Efforts have been made to employ accurate data as much as possible. However, the ultimate objective was to assess the general validity of the model as a strategic tool, not to produce a precise planning document for the two test cases.

Using the POM, stochastic solutions have been obtained for the two test cases, for a range of fixed budgets from a low of \$8 million to a maximum of \$200 million. The results validate the model’s usefulness as a source of strategic guidance. In smaller-scale incidents, such as the less serious scenarios in both test cases, it appears that regional, state and local response capabilities, in partnership with federal agencies such as DOD and FEMA, would be adequate to meet requirements, without the need for major support from commercially contracted transportation. In contrast, substantial transportation

resources and assets from the private sector would be required to adequately respond to larger incidents, such as a major hurricane with subsequent flooding. The extensive infrastructure and capabilities resident in commercial cargo carriers such as FedEx and UPS are simply not replicable in the public sector.

The POM uses mathematical optimization techniques to maximize the expected number of rescued survivors, subject to a penalty for unmet commodity demands. Using notional data, the model results show that there is a diminishing rate of return in terms of rescued survivors as the budget is increased. At higher budget levels, the incremental cost per survivor rescued is considerably greater than the cost per survivor at moderate and low budget levels. The results also show that certain conditions will create pockets of unsaveable survivors. In the hurricane test case, widespread flooding has this effect. The shutdown of Reagan National and degradation of access routes into the city results in delays in delivering needed commodities, rescue workers, and health care personnel to hard-hit areas. As a consequence, some victims die before they can be supplied or triaged on-site, or evacuated to unaffected areas. This phenomenon creates difficult policy choices for government officials. Small budget increases are unlikely to have much effect, and the larger amounts necessary to buy, for example, more rescue helicopters may not be viable for reasons of politics, fiscal constraints, or legal prohibitions.

The broader point is that money is not a panacea. Officials in Aceh, Indonesia had difficulty delivering to tsunami survivors the vast amounts of food, medicine and potable water that arrived *en masse* on the cargo aircraft of the world's richest countries. The regional capital, Banda Aceh, has only one airstrip. Until several days after the tsunami hit, it had only one functioning forklift truck.¹³⁴ No amount of money could solve that problem on Day 2 of the relief effort. Instead, a long-term strategy that emphasized requirements and capacities was in order. A functional strategy would answer two seminal questions: what items and how much of each will survivors need, and what manpower and equipment will be needed to deliver it?

¹³⁴ "Quality Over Quantity," *The Economist Global Agenda* (2005), http://www.economist.com/PrinterFriendly.cfm?Story_ID=3535065 (accessed March 2007).

This is precisely the purview of the POM. By giving planners and policymakers a template for forecasting commodity and worker needs as well as facility and equipment requirements, the POM alters the fundamental humanitarian relief question from “How much can we send?” to the more useful “What, and how much, do they need?”

At this stage of its development, the POM is a useful, though rudimentary, analytical tool. The model could be improved in a number of ways to make it more user-friendly, more accurate, and more useful. Some of these suggested improvements are enumerated in Captain Tean’s thesis. The more salient include:

- Improving the fidelity of the input data.
- Adding the ability to test alternative objective functions.
- Extending the period of observation beyond the 72-hour window immediately following the incident.
- Adding a graphical user interface for easier data input and more intuitive output displays.
- Refining and expanding parameter categories. Captain Tean suggests adding a class of survivors who need to be evacuated, but do not need medical attention.¹³⁵ Other refinements might include further subdividing workers into specialties, such as US&R team members or communications experts, and adding a separate category for truck drivers and aircrew members.

Apart from improving the model itself, the next step in POM development should incorporate some additional processes. These include:

- Operational validation of the model by logistics planners, using real-world data and a variety of test cases, scenarios and probabilities
- Integration of the POM with other analytical tools, such as FEMA’s HAZUS-MH loss estimation software, to build a complete operational picture of particular test cases through the entire disaster life cycle
- Establishment of user groups and communities of practice to share improvements to the model and best practices for its employment
- Development of partnerships with commercial air and land freight carriers, and distribution of the model to these partners

¹³⁵ Tean, *Optimized Positioning of Pre-Disaster Relief Force and Assets*, 35-36.

- Use of POM results to inform the development of requirements for state and federal contracts with private air and land freight carriers, to provide equipment, transportation and materiel support for disaster relief efforts
- Procurement of federal funding, perhaps through the Department of Homeland Security, for continued research on technological solutions to improving humanitarian supply chain management processes

A final observation: the POM is at its most powerful when it is used to detect trends and relationships. There is some marginal utility in knowing that, for example, the model chooses tractor-trailer trucks to deliver all commodities after a WMD attack, given a \$40 million budget. There is exponentially more value in knowing that the POM makes the same choice at all budget levels, if land routes are accessible. Accordingly, to achieve its full potential, the POM needs to be stretched; that is, run multiple times with different conditions, alternately varying different parameters and tinkering with the assumptions. For example, the model might be run assuming different levels of resource commitments from commercial cargo carriers. Or, it might be instructive to compare the model's results in the Washington, D.C. hurricane scenario as different combinations of road and bridge closings are simulated.

It is hoped this thesis will inspire some within the logistics and the operations research communities to take this model and improve upon it, or develop a better one. Ultimately, no matter the elegance or utility of the POM or any other model, it is only a tool. However, used judiciously, it can prompt the sort of strategic changes that will reduce, and potentially eliminate, the gap of pain.

APPENDIX A. TRANSPORTATION MEANS DATA SUMMARY

Name	Type	Number Available	Maximum Expansion	Cargo capacity (ft ³ x 1000)	Survivor capacity	Worker capacity	Hours available (3 days)	Operating range (hours)
CH-53S	Rescue helicopter	20	20	0	24	0	60	8
CH-53G ¹³⁶	General purpose helicopter	20	20	1.530	0	55	60	8
MV-22S	Rescue VSTOL aircraft	15	20	0	12	0	60	10
MV-22G ¹³⁷	General purpose VSTOL aircraft	25	20	0.858	0	24	60	10
C-130J ¹³⁸	Cargo aircraft	24	36	4.551	0	92	60	5
C-17 ¹³⁹	Cargo aircraft	24	36	8.736	0	102	60	5.33
B747 ¹⁴⁰	Cargo aircraft	5	4	6.190	0	366	60	14.23
DC-10 ¹⁴¹	Cargo aircraft	12	8	4.618	0	0	60	6.14
A300 ¹⁴²	Cargo aircraft	16	11	13.822	0	0	60	5.47
MD-11 ¹⁴³	Cargo aircraft	15	10	21.100	0	0	60	8.21
Tractor trailer ¹⁴⁴	Cargo vehicle	56	300	5.256	0	3	63	16.5
Box Van ¹⁴⁵	Cargo vehicle	56	500	1.300	0	3	63	10
Passenger bus ¹⁴⁶	Passenger vehicle	56	250	0	56	56	63	12

¹³⁶ “CH-53 Sea Stallion,” GlobalSecurity.org, <http://www.globalsecurity.org/military/systems/aircraft/h-53-specs.htm> (accessed February 2007).

¹³⁷ “Bell Boeing V-22 Osprey,” *Jane’s Defence Weekly* (12 December 2000), http://www.janes.com/defence/news/jdw/jdw001212_3_n.shtml (accessed February 2007).

¹³⁸ “C-130 Hercules,” U.S. Air Force, <http://www.af.mil/factsheets/factsheet.asp?id=92> (accessed February 2007); “C-130J Specifications and Performance,” GlobalSecurity.org.

¹³⁹ “C-17 Globemaster III,” U.S. Air Force, <http://www.af.mil/factsheets/factsheet.asp?id=86> (accessed February 2007).

¹⁴⁰ “747 Family: Technical Specifications,” The Boeing Company.

¹⁴¹ “DC-10 Technical Specifications,” The Boeing Company.

¹⁴² “Airbus A300-600,” CivilAviation.eu.

¹⁴³ “Cargo Aircraft Facts: MD11,” Air Charter Service Plc; “MD-11 Freighter Background,” The Boeing Company.

¹⁴⁴ Wright, e-mail.

¹⁴⁵ Ibid.

¹⁴⁶ Ibid.

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APPENDIX B. ENROUTE TIME SUMMARY

Transportation Means.RL	RFK Stadium	Reagan National	Dulles IAP	National Mall
	<i>a1</i>	<i>a2</i>	<i>a3</i>	<i>a4</i>
CH-53S. <i>l</i> ₁	4.39	4.35	4.28	4.36
CH-53S. <i>l</i> ₂	2.77	2.73	2.60	2.75
CH-53S. <i>l</i> ₃	2.91	2.87	2.74	2.89
CH-53S. <i>l</i> ₄	0.65	0.69	0.78	0.68
<i>l</i> ₁ = Memphis IAP <i>l</i> ₂ = Louisville IAP <i>l</i> ₃ = Indianapolis IAP <i>l</i> ₄ = Philadelphia IAP				
CH-53G. <i>l</i> ₁	4.39	4.35	4.28	4.36
CH-53G. <i>l</i> ₂	2.77	2.73	2.60	2.75
CH-53G. <i>l</i> ₃	2.91	2.87	2.74	2.89
CH-53G. <i>l</i> ₄	0.65	0.69	0.78	0.68
MV-22S. <i>l</i> ₁	2.75	2.73	2.68	2.74
MV-22S. <i>l</i> ₂	1.74	1.71	1.63	1.72
MV-22S. <i>l</i> ₃	1.83	1.80	1.72	1.81
MV-22S. <i>l</i> ₄	0.41	0.43	0.49	0.42
MV-22G. <i>l</i> ₁	2.75	2.73	2.68	2.74
MV-22G. <i>l</i> ₂	1.74	1.71	1.63	1.72
MV-22G. <i>l</i> ₃	1.83	1.80	1.72	1.81
MV-22G. <i>l</i> ₄	0.41	0.43	0.49	0.42
C-130J. <i>l</i> ₁		2.19	2.16	
C-130J. <i>l</i> ₂		1.52	1.46	
C-130J. <i>l</i> ₃		1.58	1.52	
C-130J. <i>l</i> ₄		0.67	0.71	
C-17. <i>l</i> ₁		1.84	1.82	
C-17. <i>l</i> ₂		1.30	1.26	
C-17. <i>l</i> ₃		1.35	1.31	
C-17. <i>l</i> ₄		0.62	0.65	
B747. <i>l</i> ₁		1.75	1.73	
B747. <i>l</i> ₂		1.24	1.20	
B747. <i>l</i> ₃		1.29	1.25	
B747. <i>l</i> ₄		0.61	0.64	

Transportation Means.RL	RFK Stadium	Reagan National	Dulles IAP	National Mall
	<i>a1</i>	<i>a2</i>	<i>a3</i>	<i>a4</i>
DC-10. <i>l</i> ₁		1.61	1.59	
DC-10. <i>l</i> ₂		1.16	1.12	
DC-10. <i>l</i> ₃		1.20	1.16	
DC-10. <i>l</i> ₄		0.59	0.61	

A300. <i>l</i> ₁		1.74	1.72	
A300. <i>l</i> ₂		1.24	1.20	
A300. <i>l</i> ₃		1.29	1.24	
A300. <i>l</i> ₄		0.61	0.64	

MD-11. <i>l</i> ₁		1.68	1.65	
MD-11. <i>l</i> ₂		1.20	1.16	
MD-11. <i>l</i> ₃		1.24	1.20	
MD-11. <i>l</i> ₄		0.60	0.62	

Tractor trailer. <i>l</i> ₁	14.70	14.65	14.40	14.65
Tractor trailer. <i>l</i> ₂	10.27	10.17	10.00	10.17
Tractor trailer. <i>l</i> ₃	10.15	10.05	9.87	10.05
Tractor trailer. <i>l</i> ₄	2.13	2.25	2.53	2.20

Box Van. <i>l</i> ₁	22.70	22.65	22.40	22.65
Box Van. <i>l</i> ₂	18.27	18.17	10.00	18.17
Box Van. <i>l</i> ₃	18.15	18.05	9.87	18.05
Box Van. <i>l</i> ₄	2.13	2.25	2.53	2.20

Passenger bus. <i>l</i> ₁	22.70	22.65	22.40	22.65
Passenger bus. <i>l</i> ₂	10.27	10.17	10.00	10.17
Passenger bus. <i>l</i> ₃	10.15	10.05	9.87	10.05
Passenger bus. <i>l</i> ₄	2.13	2.25	2.53	2.20

NOTES:

* Aircraft flight time calculations are increased 25 minutes for takeoff and landing (distance shortened 15 miles); helicopter and VTOL aircraft enroute times are not adjusted

* For land transportation methods, 8 hour rest period is added where enroute time exceeds max operating range in hours (see Appendix A)

* Blank cell indicates infeasible route (excessive distance or mismatched means and destination type)

APPENDIX C. POM RESULTS SUMMARY (WMD)

Budget (\$M)	Unrescued Survivors (ω_1)	Unrescued Survivors as % of Total (ω_1)	Unrescued Survivors (ω_2)	Unrescued Survivors as % of Total (ω_2)	Undelivered Commodities (ω_1) (ft ³ x 1000)	Undelivered Commodities (ω_2) (ft ³ x 1000)	Budget Spent (ω_1) (\$)	Budget Spent (ω_2) (\$)
8	3372	13.49%	0	0.00%	0	0.00	7,500,000	7,500,000
10	3108	12.43%	0	0.00%	0	0.07	9,895,358	10,000,000
12	3053	12.21%	0	0.00%	0	0.07	12,000,000	6,904,642
15	2592	10.37%	56	0.37%	0.38	0.00	14,050,000	14,050,000
20	2232	8.93%	0	0.00%	0	0.07	20,000,000	17,504,642
25	1628	6.51%	88	0.59%	4.24	4.61	24,894,000	24,894,000
30	1368	5.47%	0	0.00%	0.2	0.00	29,981,000	22,181,000
35	880	3.52%	0	0.00%	0	0.07	35,000,000	22,035,946
40	348	1.39%	0	0.00%	0	0.07	40,000,000	21,835,946
45	204	0.82%	0	0.00%	0	0.07	45,000,000	10,638,796
50	191	0.76%	0	0.00%	0	0.07	50,000,000	10,239,836
55	136	0.54%	0	0.00%	0	0.07	55,000,000	10,039,836
60	0	0.00%	0	0.00%	0	0.07	60,000,000	9,839,836
65	0	0.00%	0	0.00%	0	0.07	60,486,676	10,326,512
70	0	0.00%	0	0.00%	0	0.07	60,486,676	10,326,512
80	0	0.00%	0	0.00%	0	0.07	68,849,108	10,326,512
90	0	0.00%	0	0.00%	0	0.07	68,849,108	10,326,512
100	0	0.00%	0	0.00%	0	0.07	68,849,108	10,326,512
150	0	0.00%	0	0.00%	0	0.07	68,849,108	16,623,200
200	0	0.00%	0	0.00%	0	0.07	68,849,108	16,623,200

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APPENDIX D. POM RESULTS SUMMARY (HURRICANE)

Budget (\$M)	Unrescued Survivors (ω_1)	Unrescued Survivors as % of Total (ω_1)	Unrescued Survivors (ω_2)	Unrescued Survivors as % of Total (ω_2)	Undelivered Commodities (ω_1) (ft ³ x 1000)	Undelivered Commodities (ω_2) (ft ³ x 1000)	Budget Spent (ω_1) (\$)	Budget Spent (ω_2) (\$)
8	3924	15.70%	0	0.00%	945.46	0.00	8,000,000	5,902,400
10	3924	15.70%	20	0.29%	885.60	0.29	10,000,000	8,516,672
12	3924	15.70%	0	0.00%	821.10	0.00	12,000,000	11,102,976
15	3895	15.58%	24	0.34%	743.12	0.00	15,000,000	14,032,680
20	3860	15.44%	0	0.00%	651.84	0.00	20,000,000	15,230,742
25	3852	15.41%	0	0.00%	546.98	0.00	25,000,000	23,889,600
30	3924	15.70%	0	0.00%	443.48	0.00	30,000,000	30,000,000
35	3937	15.75%	0	0.00%	344.39	0.00	35,000,000	34,493,504
40	3957	15.83%	0	0.00%	252.79	0.00	40,000,000	39,689,280
45	3948	15.79%	0	0.00%	154.45	0.00	45,000,000	42,875,456
50	3861	15.44%	0	0.00%	103.31	0.00	50,000,000	49,073,830
55	3612	14.45%	0	0.00%	24.51	0.00	55,000,000	53,643,088
60	3209	12.84%	0	0.00%	29.27	2.12	60,000,000	19,793,856
65	2864	11.46%	0	0.00%	1.54	0.06	65,000,000	19,820,008
70	2468	9.87%	0	0.00%	27.16	0.00	70,000,000	15,316,486
80	1356	5.42%	0	0.00%	1.66	11.90	80,000,000	54,391,552
90	428	1.71%	0	0.00%	23.53	0.00	90,000,000	54,718,720
100	36	0.14%	0	0.00%	1.65	0.00	100,000,000	100,000,000
150	16	0.06%	0	0.00%	0.00	0.00	150,000,000	17,238,254
200	0	0.00%	0	0.00%	0.00	0.00	157,613,970	16,532,224

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