Cooperative Mobility for Competitive Megaregions

The Effect of Shadow Evacuation in Megaregion Disasters: A Pilot Study

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16. Abstract

Transportation systems serve important roles during emergencies, in particular for evacuations. However, efficient travel during these life-and-death scenarios can be adversely impacted by external conditions, such as unnecessary and unneeded travel. This research sought to enhance the understanding of the effects of these conditions by analyzing shadow evacuations, and their impact on regional traffic operations in megaregions, more broadly. The research was based on simulations of a range of hurricane evacuation threat scenarios in the Gulf of Mexico building upon prior study using *TRANSIMS*. These assessments are also targeted at what many assume could be worst-case evacuation conditions and pushing the limits of current simulation modeling capability. Among the broader findings of this work was that shadow evacuation participation rates did not significantly impact the evacuation clearance times within mandatory evacuation areas of the megaregion as long as demand could be temporarily spread out. This finding does not, however, suggest that the shadow evacuations have no impact on evacuation processes. High rates of shadow evacuees can cause significant congestion if they are not able to exit critical routes before mandatory evacuees reach areas further away from the coast.

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Table of Contents

Chapter 1. Introduction

Natural disasters like hurricanes, floods, and wildfires occur throughout the world. And while they can occur anywhere, coastal areas tend to be the most vulnerable and tend to receive the most attention. Over the last decade or so, another set of areas, referred to as megaregions, have also received growing interest. Megaregions are broadly defined as continuously populated regions of once-separate metropolitan areas that have grown together. They often cover hundreds of miles and can even cross national boundaries. Megaregions can also be susceptible to a range of natural and manmade hazards. However, unlike coastal areas that are considered to be vulnerable based on their geography, megaregions are vulnerable because of their enormous populations and geographic extents. One example of this vulnerability is in evacuation.

During imminent life and death conditions, such as those posed by hurricanes, evacuations are used as a protective action. And although evacuations have a long track record of success, they can be complex, costly, and at times even risky. They are most effective when hazard threats are clear and evacuees obey directions of when, where, and how to evacuate. They are also best if they are small, involve travel over short distances, and all evacuees can move themselves. Evacuation in megaregions are likely to involve few, if any, of these conditions.

Difficulties associated with megaregion evacuations, also extends into how they are analyzed. Over the 30 years, the use of traffic simulation modeling has evolved to become the standard method for analyzing evacuation processes.[1] [2] [3] Since the modeling of evacuation began in the late 70's after the Three Mile Island nuclear power plant emergency, the use of simulation has become significantly more complex and powerful. Today's state of the art systems permit the modeling of hundreds of thousands of individual vehicles, moving over vast road networks, and encompass

[1] Chiu Y., Zheng, H., Villalobos J. A., Peacock W., and Henk R. (2008). Evaluating Regional Contra-Flow and Phased Evacuation Strategies for Texas: Using a Large-Scale Dynamic Traffic Simulation and Assignment Approach. *Journal of Homeland Security and Emergency Management*, Vol. 5, No. 1, Art. 34.

[2] Wolshon, B., Lefate, J., Naghawi, H., Montz, T., and Dixit, V. (2009). Application of TRANSIMS for the Multimodal Microscale Simulation of the New Orleans Emergency Evacuation Plan - Final Report. *Federal Highway Administration United States Department of Transportation.*

[3] Zhang, Z.; Spansel, K.; Wolshon, B. (2013). Megaregion Network Simulation for Evacuation Analysis. *Transportation Research Record*: *Journal of the Transportation Research Board*, No. 2397, pp. 161-170.

time durations that can include several days. However, the modeling of traffic processes at the megaregion level, pushes even the best of these technologies to their limits.

This paper summarizes the methods used for and results gained from simulations of megaregion evacuations. Specifically, the simulation models were used to assess the effects of varying levels of shadow evacuation participation during a range of threat conditions associated with hurricanes in the Gulf of Mexico. The research described here builds upon prior study[3] that originally applied the agent-based traffic modeling system *TRANSIMS* to examine megaregion evacuation traffic management techniques along the Gulf Coast of the United States (U.S.). Similar to the original studies, however, this research has applied the model to assess what many assume could be worst case evacuation conditions and attempts to push the limits of current simulation modeling capability.

This work is also aimed at providing a better understanding, in general, of megaregion transportation systems. In the past, research into transportation issues at the megaregion level has been focused on broader topics like freight flow patterns, land use policies, economic ties, and general travel issues within and across these areas for infrastructure investment and general decision-making.[4] [5] [6] However, emergency preparedness has also been identified as an issue at the megaregion level which can impact their economic competiveness.[5] This project uses an evacuation as a testbed to examine operations more specifically, based on individual vehicles on specific route segments and how their interactions and travel over large times and spaces resulted in patterns of congestion and delay.

Interest in shadow evacuations has existed since the earliest days of evacuation planning. Shadow evacuees are broadly defined as people who evacuate even when not under a direct order to do so. Shadow evacuations occur for a variety of reasons, but are heavily influenced by perceptions that

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[4] Harrison, R., Johnson, D., Loftus-Otway, L., Hutson, N., Seedah, D., Zhang, M., and Lewis, C. (2012). Megaregion Freight Planning: A synopsis. *Texas Department of Transportation*. Final Report: FHWA/TX-11/0-6627-1.

[5] Ducca, F., Ma, T., Mishra, S., Welch, T., Donelly, R., Weidner, T., Moeckel, R., Moore, T., Pozdena, R., Deal, B., Chakraborty, A., Simmonds, D., Yoder, S. (2013). A framework for Megaregion Analysis: Development and Proof of Concept. *National Center for Smarth Growth and Education at the University of Maryland.*

[6] Wang Y, Wu B, Dong Z, Ye X. (2016). A Joint Modeling Analysis of Passengers' Intercity Travel Destination and Mode Choices in Yangtze River Delta Megaregion of China. *Mathematical Problems In Engineering*, pp. 1-10.

an impending hazard can result in direct harm to themselves and their property, whether that is actually the case or not. From a transportation perspective, understanding the effect of shadow evacuations is important for a number of reasons.[7] [8] Most obviously of these is that they produce higher travel demand and evacuation traffic volume because they result in more departures and over a much larger area than intended.[9] This, in turn, can result in higher congestion and longer clearance times. Most critically, shadow evacuations in areas downstream of a declared hazard zone can restrict if not completely impede the movement of evacuees directly affected by a hazard.

In the sections that follow, key aspects and findings from this study are highlighted. This starts with a review and summary of important prior work related to evacuations, traffic simulation, and shadow evacuations, especially as they relate to megaregions. Next, attention shifts to the key methods and assumptions of the work, including the data, means, and methods used to build the simulation models and run them. This is followed by the results and analysis of the simulation output. As the goal of the project was to assess traffic conditions associated with shadow evacuations in megaregion under hurricane threats, performance measures like evacuation clearance times and volume to capacity ratios were used. Finally, these results are assessed to see the broader trends and key applicable results of the work. Although this work was theoretical, the model results can be used to illustrate important real-life trends and relationships between road capacity and evacuation travel demand. This, in turn, could be used to better understand how to plan for such events and maintain efficient traffic flow for the development of effective disaster evacuation plans across local, state, and megaregion levels.

[7] Murray-Tuite, P., Wolshon, B. (2013). Evacuation transportation modeling: An overview of research, development, and practice. *Transportation Research Part C,* Vol. 27, pp. 25-45.
[8] Lindell, M., Perry, R. (2012). The protective action decision model: theoretical modifications and additional evidence. *Risk Analysis*, 32 (4), pp. 616-632.
[9] Zeigler, D.J., Brunn, S.D., and Johnson, J. H. Jr. (1981). Evacuation from a Nuclear Technological Disaster. *Geographical Review*, 71, pp. 1-16.

Chapter 2. Literature Review

Over the past decade, megaregion transportation research has included work related to hazards, emergencies, and disasters – most notably on evacuations. This has also included megaregion evacuation modeling and analysis under various proactive evacuation traffic management strategies, such as contraflow,[10] [11] [12] and various demand levels with consideration of shadow evacuation.

Among the earliest shadow evacuation research was associated with the effect of shadow evacuation as part of the Three Mile Island (TMI) nuclear power plant emergency.[7] Additional research on shadow evacuations was related to hurricanes and other large-scale natural hazards.[13] [14] [15] Research has also attempted to quantify shadow participation and extent[15], however this has been proven difficult because people in shadow areas evacuate at their own risk and are not always monitored by emergency responders. Thus, there is limited knowledge is available and data are typically developed some time after the incident.

The overresponse to evacuation orders for Hurricane Rita in 2005 has often been described as a large shadow evacuation that caused massive congestion and gridlock. As such, many residents chose to return home rather than continue their evacuation. However, the large shadow evacuation was related to the evacuation orders for Hurricane Rita. Because of this, residents believed that they were within the hazard area and that they had been ordered to evacuate. The biggest failure of the Hurricane Rita evacuation was the communication the public.[16] In addition, the devastation

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[10] Theodoulou, G. (2003). Contraflow Evacuation on the Westbound I-10 out of the City of New Orleans. MS thesis. *Louisiana State University*, Baton Rouge.
[11] Lim, E., and B. Wolshon. (2005). Modeling and Performance Assessment of Contraflow Evacuation Termination Points. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1922, pp. 118–128.
[12] Chiu, Y., H. Zheng, J. A. Villalobos, W. Peacock, and R. Henk. (2008). Evaluating Regional Contra-Flow and Phased Evacuation Strategies for Texas Using a Large-Scale Dynamic Traffic Simulation and Assignment Approach. *Journal of Homeland Security and Emergency Management*, Vol. 5, No. 1.
[13] NUREG/CR-6864, (2005). Identification and Analysis of Factors Affecting Emergency Evacuations. *U.S. Nuclear Regulatory Commission*.
[14] Baker, E. J. Hurricane Evacuation Behavior. (1991). *International Journal of Mass Emergencies and Disasters*. Vol. 9, No. 2, pp. 287-310.
[15] Mitchell, J.T., Edmonds, A.S., Cutter, S. L., Schmidtlein, M., McCarn, R., Hodgson, M.E., and Duhé, S. (2005). Evacuation Behavior in Response to the Graniteville, South Carolina, Chlorine Spill. Quick Response Research Report 178. Boulder, CO: *Natural Hazards Center, University of Colorado*.

from Hurricane Katrina weeks before could have influenced this response. Hurricane Ike was the next major hurricane following Hurricane Rita. The lower shadow evacuation observed was attributed to improved offsite response messaging.[16] However, the results are difficult to interpret because research can define shadow evacuation differently.[17] [18] [19] Although shadow evacuation has been defined broadly as people who evacuate even when not under a direct order to do so, some research interchanged spontaneous evacuation and shadow evacuation terms which may have contributed to its misuse.[20]

Shadow evacuations are defined by some to be “spontaneous,” because residents leave without having been ordered to do so. However, the definition of spontaneous evacuation is more appropriately applied to residents who leave before the official evacuation advisory is issued. This includes those who observe or receive direct information on the hazard and respond prior to any issuance of a protective protocol. Thus, it has a temporal component that the generally accepted definition of shadow evacuation does not.

In post-evacuation research of the 2005 Graniteville train accident, which had a declared evacuation area of one-mile radius, it was observed that 59 percent of the residents from outside the one-mile radius also evacuated as shadow.[19] However, the study also noted that more than half of these residents were specifically instructed to evacuate, mostly from Reverse 911 or fire/police officials knocking on their doors. Anyone that was directed to evacuate should not have been included in the shadow contribution, because of this was not due to the tendency of the advisory to cause evacuation.

This research was motivated by a need to continue the evolution of the understanding of shadow evacuation processes. The work presented here is based on simulation using an agent-based

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[16] Lindell, M., Prater, C., Wu, H., Siebeneck, L. (2012). Household Evacuation Decision-Making in Response to Hurricane Ike. *Natural Hazards Review*, pp. 283-296.

[17] Ozbay, K., Yazici, M. A. (2006). Analysis of Network-wide Impacts of Behavioral Response Curves for Evacuation Conditions. *IEEE Intelligent Transportation systems Conference.*

[18] Mitchell, J.T., Cutter, S.L., and Edmonds, A. S. (2007). Improving shadow evacuation management: Case study of the Graniteville, South Carolina, chlorine spill. *Journal of Emergency Management.* 5(1). pp. 28-34.

[19] Lindell, M., Prater, C. (2007). Critical Behavior Assumptions in Evacuation Time Estimate Analysis for Private Vehicles: Examples from Hurricane Research and Planning. *Journal of Urban Planning and Development.*

[20] Zeigler, D.J., and Johnson, J. H. Jr. (1984). Evacuation Behavior in Response to Nuclear Power Plant Accidents. *Professional Geographer*, 36(2), pp. 207-215.

evacuation traffic model, *TRANSIMS* which permitted the ability to assess and evaluate traffic conditions under a consistent mandatory evacuation scenario while varying shadow participation rates to measure their effects under different evacuation conditions in the Gulf Coast megaregion.

Chapter 3. Research Methodology

Broadly, this research used simulation modeling to investigate aspects of the internal dynamics of a megaregion evacuation and the impact that shadow participation may play. This research used the Gulf Coast megaregion, spanning from New Orleans, LA in the east to Houston, TX in the west to explore the experimental methodology. In general, two cohorts of evacuees were modeled, evacuees residing within the mandatory evacuation area and shadow evacuees, residing within the greater megaregion. The scenarios developed reflect systematic variations to shadow participation rate, the proportion of megaregion residents that decide to evacuate despite not residing in the mandatory evacuation area. The following sections of this chapter describe the simulation model development and the shadow evacuation scenarios.

3.1. Simulation Model Development

TRANSIMS is an agent-based microscopic traffic simulation within which the megaregion traffic model was built. At is most fundamental level, traffic simulation models consist of a road network (streets, highways, and freeways), control measures (sign, signals, and pavement markings), and vehicles as well as the spatial and temporal relationships that link these elements together. The road network for the megaregion model was constructed using ArcMap 10 GIS software.[3] The extent of this megaregion road network is shown in Figure 3.1. As this figure shows, the megaregion encompassed six metropolitan areas and two coast areas, designated as “Coast Area 1” and “Coast Area 2.” These two coastal areas were “mandatory” evacuation areas and the six metropolitan areas were used to generate shadow evacuations that interacted with the “ordered” evacuation traffic.

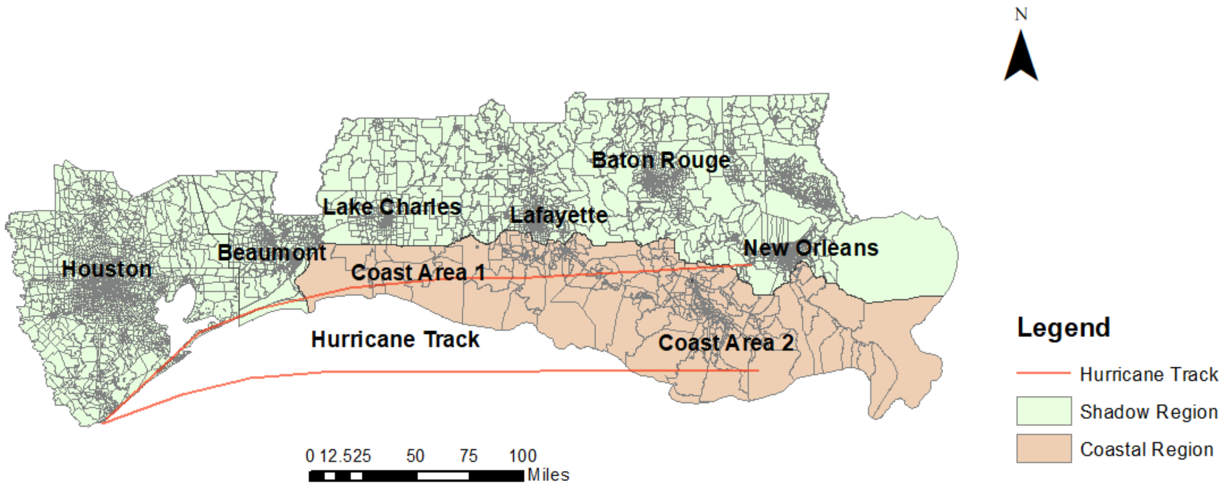


Figure 3.1. - U.S. Gulf Coast Megaregion TAZs and Hurricane Track

TRANSIMS contains a population synthesizer to estimate the evacuation demand, the number of evacuees at each origin within the model. Using the 2010 census data, the population synthesizer generated the representative traffic demand throughout the model to facilitate the evacuation. Next, a destination choice model, developed by Cheng and Wilmot,[21] was applied to forecast the destination choice for all the evacuees. These evacuees were assumed to use auto-based self-evacuation as their mode of travel. A time dependent sequential logit model (TDSLM) model, also developed by Fu and Wilmot[22] was applied to forecast the evacuation departure times. *TRANSIMS* also contains internal algorithm for modeling traffic control. This was used to generate typical traffic signal timings and operations throughout the network. It should be noted that while both the traffic demand and the signal control were modeled to be an approximate representation, they do not reflect exact field conditions. For additional details regarding model development, readers are referred to the authors prior work.[3]

[21] Cheng, G., Wilmot, C. G. and Baker, E. J. (2008). Destination Choice Model for Hurricane Evacuation. *Presented at 87th Annual Meeting of the Transportation Research Board*, Washington, D.C.
[22] Fu, H., Wilmot, C. G. and Baker E. J. (2006). Sequential Logit Dynamic Travel Demand Model and Its Transferability. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1977, pp. 17–26.

3.1.1. Scenario Development

The "base scenario" event, referred to as Scenario 1, was a single day evacuation resulting from a 1867 unnamed Category 4 storm that threatened the full Gulf Coast study area. Using the TDSLM developed by Fu and Wilmot[23] the evacuation demand for each region was estimated in response to this storm. From this bases case, five additional shadow evacuation scenarios were developed. For each scenario, the mandatory evacuation areas were selected as Coast Area 1 and Coast Area 2. The evacuation demand does change in either of these two areas, regardless of the scenario. Scenario 2 – 6, sequentially reduces the shadow participation rate among the other six areas of the megaregion. The demand generated in each of these scenarios in shown in Table 3-1.

Table 3.1: Evacuation and Shadow Evacuation Demand

Scenario	Houston	Beaumont	Lake Charles	Lafayette	Baton Rouge	New Orleans	Coast1	Coast2
1 (H0)	546,780 (14%)	41,689 (15%)	25,809 (18%)	27,936 (17%)	109,019 (32%)	206,595 (31%)	29,327 (35%)	27,917 (12%)
2 (H10)	470,333 (12%)	35,957 (13%)	22,334 (16%)	22,690 (14%)	94,229 (27%)	177,442 (27%)	29,327 (35%)	27,917 (12%)
3 (H20)	393,887 (10%)	30,224 (11%)	18,859 (13%)	17,443 (11%)	79,440 (23%)	148,289 (22%)	29,327 (35%)	27,917 (12%)
4 (H30)	317,440 (8%)	24,491 (9%)	15,383 (11%)	12,196 (7%)	64,650 (19%)	119,136 (18%)	29,327 (35%)	27,917 (12%)
5 (H40)	240,993 (6%)	18,758 (7%)	11,908 (8%)	6,950 (4%)	49,861 (14%)	89,983 (14%)	29,327 (35%)	27,917 (12%)
6 (H50)	164,546 (4%)	13,025 (5%)	8,433 (6%)	1,703 (1%)	35,071 (10%)	60,830 (9%)	29,327 (35%)	27,917 (12%)

Chapter 4. Data Analysis

The simulation results represent an average of 20 individual model iterations. These average values help to account for model stochasticity within *TRANSIMS*. The average values also help to lessen the likelihood of data interpretation being made on a single run that could have potentially produced an "outlier" result. The measures of performance that served as the bases of comparison for the simulate scenarios were evacuation clearance time, and volume to capacity ratios. Consistent with the manner in which all data were collected, the clearance times and vehicular volumes were collected and tabulated in increments of one hour.

4.1. Evacuation Clearance Time Results

To understand the effect of varying shadow population participation rates on evacuation clearance time, the cumulative percent evacuated for each time interval was calculated for both the coastal regions under mandatory evacuation and for the entire shadow region. The cumulative percent evacuated from each coastal zone are provided in Figure 4.1. Also shown in the figure is the evacuation loading curve, for reference.

The vertical distance between the cumulative percent evacuated and the loading curve represent the approximate number of evacuees in the network at a given time. The horizontal distance between these curves represents the travel time including any additional delay induced by traveling through the network. From the figure, it can be seen the cumulative percent evacuating the coastal regions were not impacted by the shadow participation rate. That is to say, the shadow participation rate occurring within the megaregion did not significantly delay the evacuees from exiting the coastal region. As these evacuees exited the coast regions and traveled through the remainder of the megaregion, their travel was likely delayed, maybe even significantly. However, their ability to exit the mandatory evacuation area, was not significantly affected.

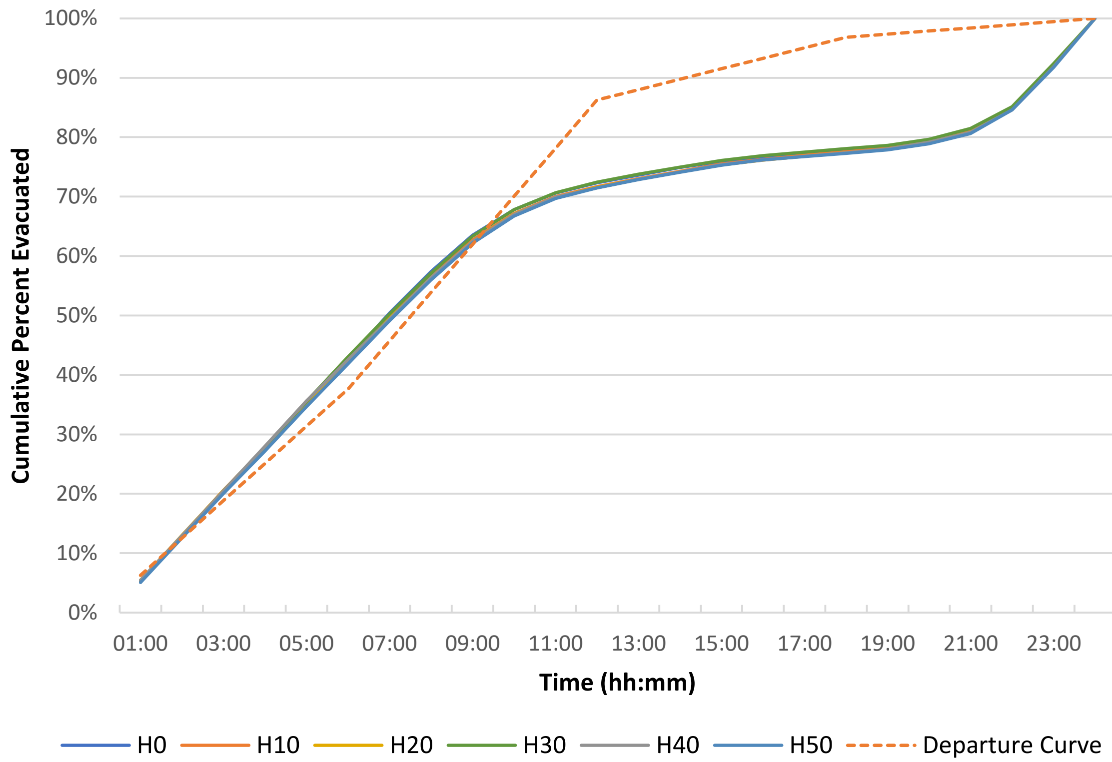


Figure 4.1. - Cumulative Percent Evacuated from Coast1 and Coast2

Figure 4.2. shows the cumulative percent evacuated from the entire megaregion modeled (inclusive of the coastal areas). The figure suggests significant delays occurred in the model when the shadow participation rate was increased by more than 30 percent. The discrepancies between the models began at approximately 5:00 AM and continued until approximately 3:00 PM. However, the total time required to evacuate 90 percent and 100 percent of the population was not impacted by the shadow evacuation. This suggest that while increasing the shadow participation rate beyond 30 percent did adversely impact the evacuation, it did not have an overall effect on the clearance time. This was likely because the last ten percent of the evacuees (the evacuation tail) tend to take longer to mobilize, load onto the network, and ultimately exit. Because of the delays which naturally occur during the evacuation tail, the vehicles that were delayed by the increased shadow participation rate where able to “catch up” to the evacuees in the other scenarios and exit at approximately the same time.

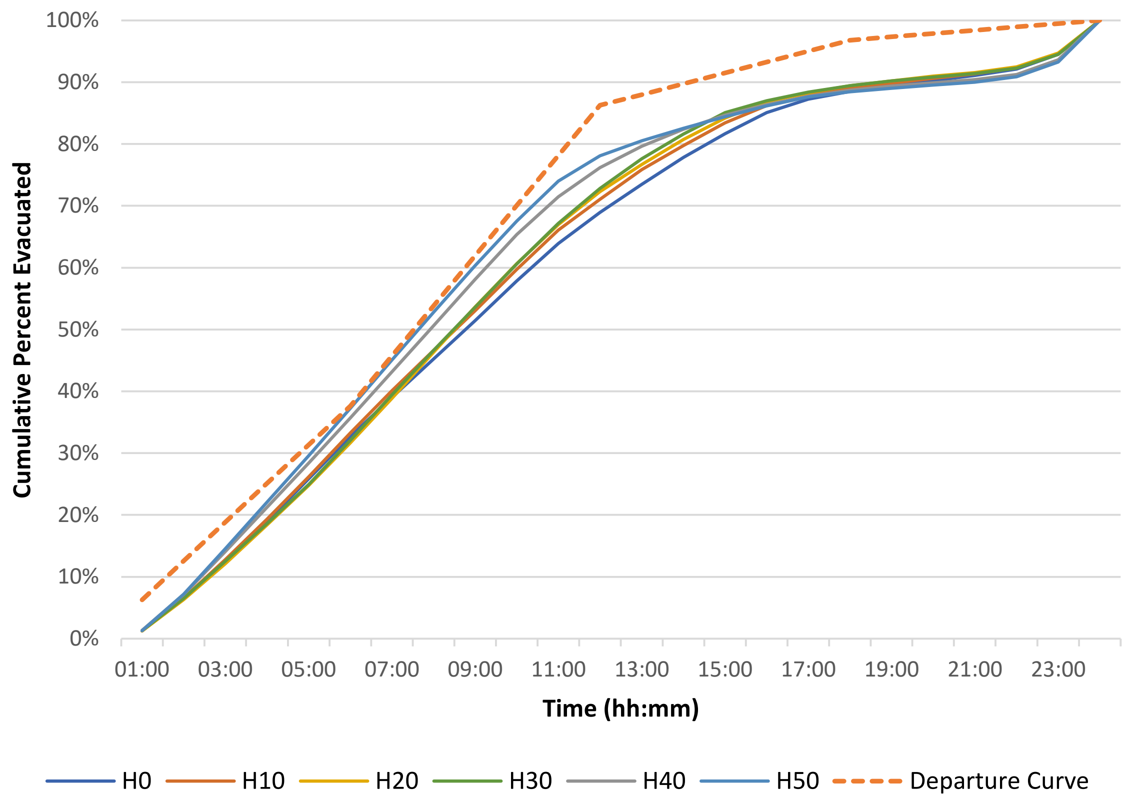


Figure 4.2. - Cumulative Percent Evacuated from the Megaregion

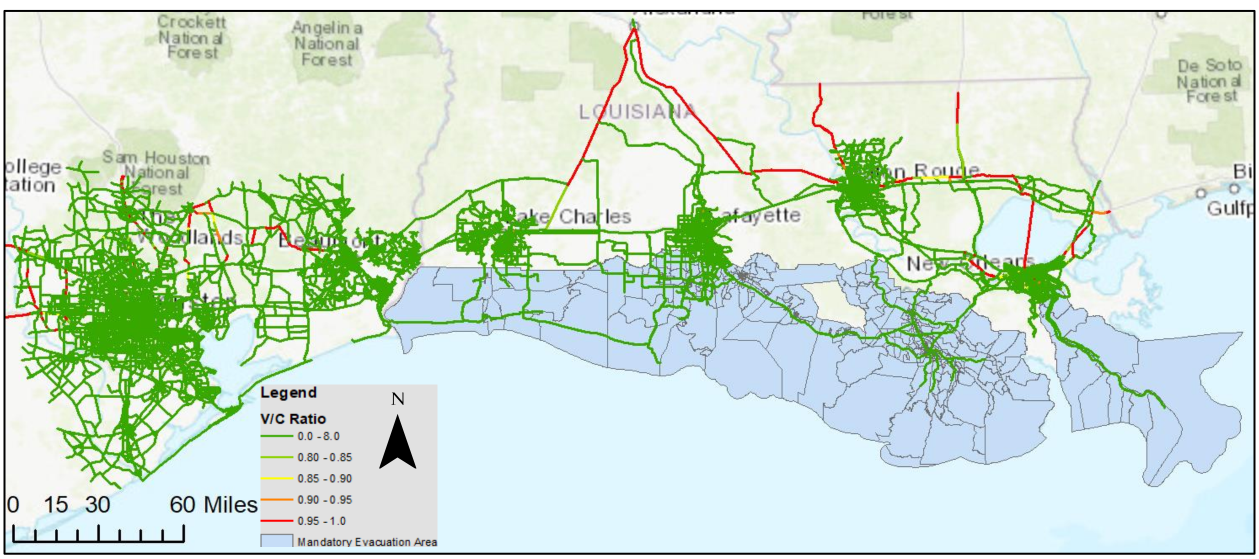
Overall, the analysis of the evacuation clearance time suggested that shadow participation rates at or below 30 percent did not significantly impede the movement of traffic. Furthermore, when investigating the time required to evacuate 90 percent or more of the population, it does not appear that the shadow participation rate had any impact on the evacuation clearance time. This analysis also found that the shadow participation rate did not impact the ability of residents within the mandatory evacuation zones to exit these zones. While these evacuees would have likely encountered congestion within the greater megaregion, the ability to evacuate the area of highest danger was not impacted.

4.2. Volume to Capacity Ratio

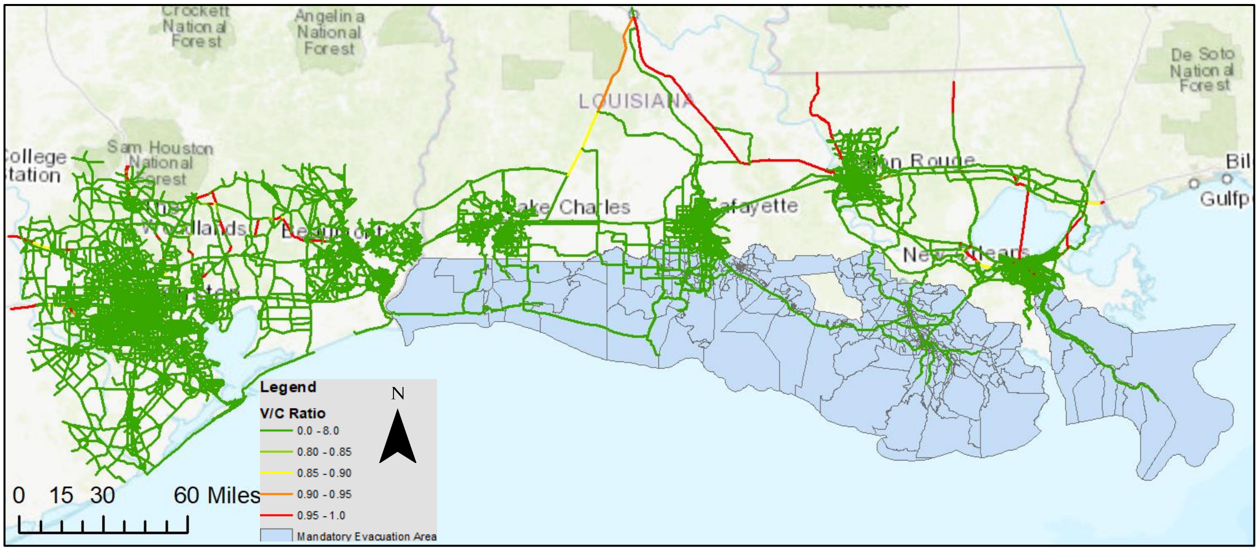
The volume to capacity ratio (v/c) is used to measure congestion levels. Volume refers to the rate at which vehicles travel on a road. Volume is generally provided in vehicles per hour. The capacity of a road is the maximum achievable volume that can be serviced. The ratio of volume and capacity is widely used in traffic engineering practice as a measure of the congestion level on a roadway. The v/c has a maximum value of 1.0, suggesting the road is at or near capacity and a minimum value of zero when no vehicles are on the road.

In this research, v/c ratios for the first six hours into the evacuation and during one of the most congested periods during the evacuation for each scenario are shown in Figure 4.3. The network links are color coded according to their v/c ratios. Dark green represents links with a v/c less than 0.8, light green for a v/c between 0.8 and 0.85, yellow for a v/c between 0.85 and 0.9, orange for a v/c between 0.9 and 0.95; and red for a v/c between 0.95 and 1.0.

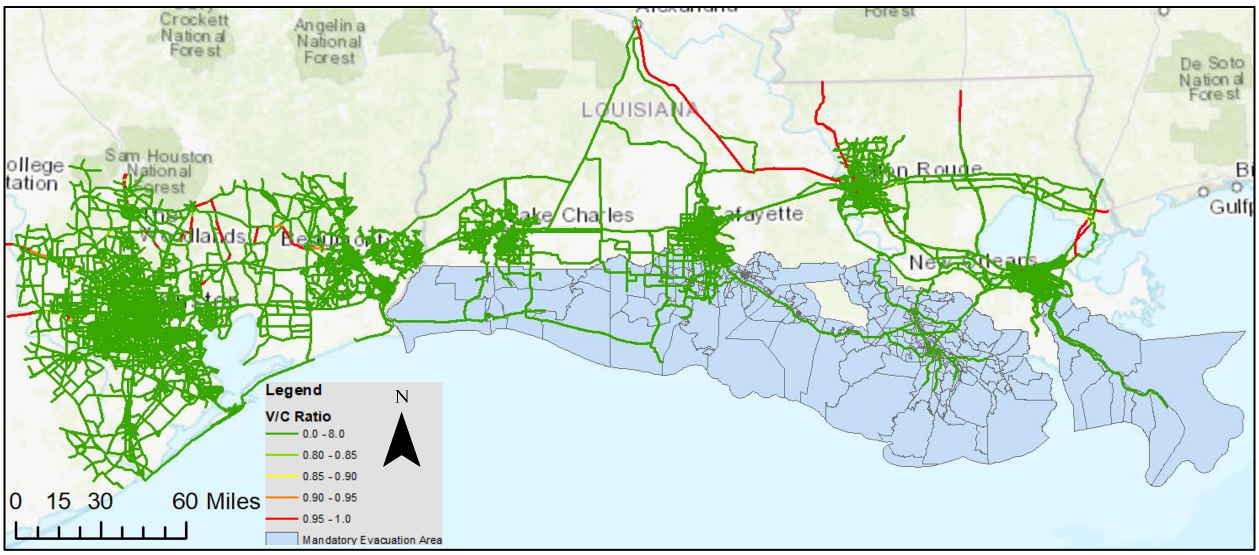
In general, high v/c ratios were observed on links leading out of the network. This was an expected finding because vehicles from throughout the megaregion converged to these locations as they tried to exit the network. It can also be seen in the figure that scenarios with higher shadow participation resulted in more links having higher v/c ratios and thus more links being represented with yellow, orange, and red. This results was also expected because as the shadow evacuees increased the volume on exit links.



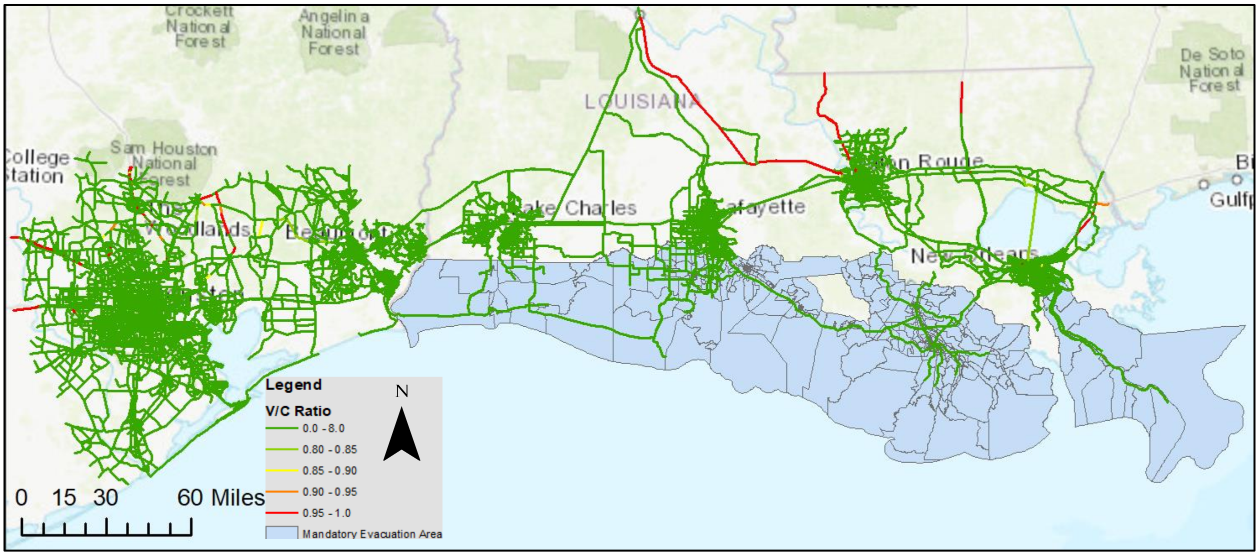
(a) Volume to Capacity Ratio for Scenario 1



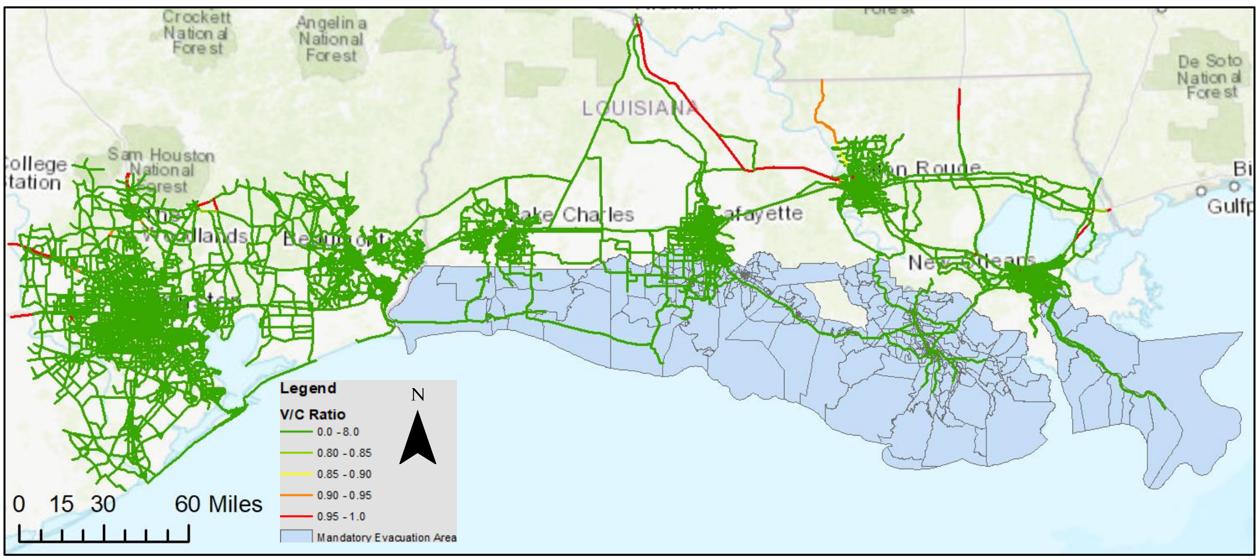
(b) Volume to Capacity Ratio for Scenario 2



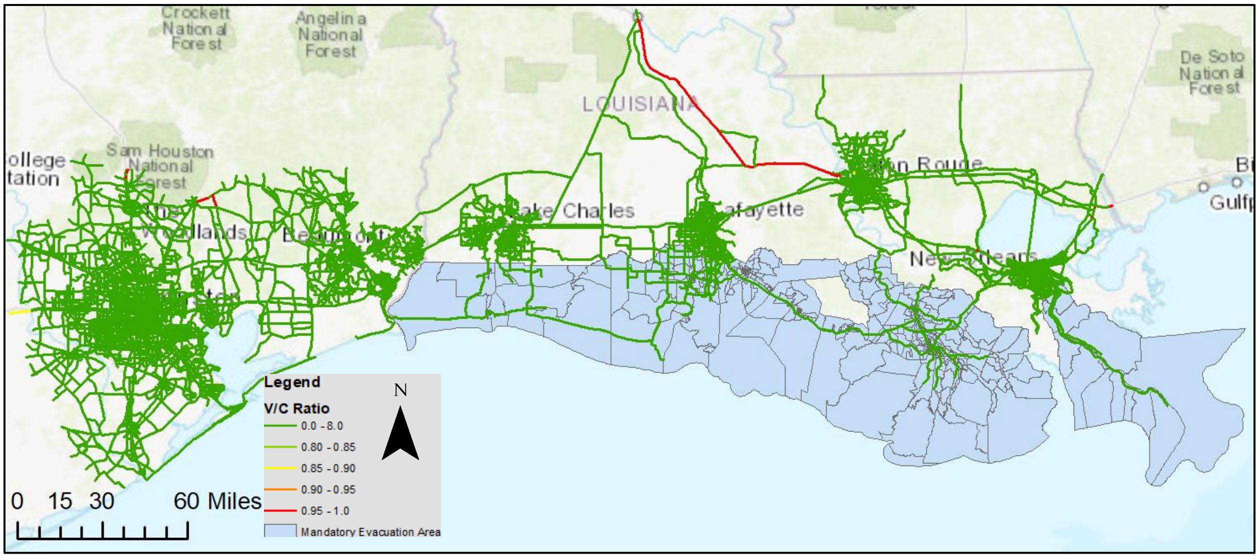
(c) Volume to Capacity Ratio for Scenario 3



(d) Volume to Capacity Ratio for Scenario 4



(e) Volume to Capacity Ratio for Scenario 5



(f) Volume to Capacity Ratio for Scenario 6
Figure 4.3. - Megaregion Volume to Capacity Ratios

Chapter 5. Conclusion and Recommendations

Transportation systems serve important roles during emergencies, in particular for evacuations. However, efficient travel during these life-and-death scenarios can be adversely impacted by external conditions, such as unnecessary and unneeded travel. This research sought to enhance the understanding of the effects of these conditions by analyzing shadow evacuations and their impact on regional traffic operations and more broadly use traffic simulation to examine traffic in megaregions.

Among the broader and unexpected findings of this work was that shadow evacuation participation rates did not significantly impact the evacuation clearance times within mandatory evacuation areas of the megaregion. As the evacuees departed the mandatory evacuation area, they did not immediately encounter significant amounts of congestion. This is because the population is distributed throughout the megaregion, resulting in the shadow evacuees also being spread out. Had the evacuees, leaving the mandatory evacuation area been confronted with all the shadow participants, all at once and in the same region, the results would likely suggest an impact on clearance times. However, because the shadow evacuees reside through the region, congestion immediately outside of the mandatory evacuation area was not significantly increase by the shadow evacuees.

Another somewhat surprising finding was that the shadow evacuation also did not increase the 90 percent or 100 percent evacuation clearance times within the megaregion, as a whole. This likely has to do with the behavior of the evacuation "tail". The time required to plan, prepare, and depart for an evacuation varies from person to person. Some evacuees will enter the network quicker, while others will take longer. The evacuation "tail" represent those individuals who take significantly longer to begin their evacuation. As congestion built within the megaregion as a result of increasing the number of shadow evacuees, many vehicles were delayed. However, the delay incurred by the added shadow evacuees was less than the delay that results from the evacuation tail. In this sense, it could be said that the evacuees, delayed by the increase shadow participation rate, were able to "catch-up" to the evacuation tail due to the longer loading periods seen toward the end of the evacuation.

These results, however, should not suggest that the shadow evacuation had no impact on the evacuation process. Significant congestion was seen throughout the model, particularly on roads exiting the megaregion. This was due to evacuees from all over the megaregion converging on to a few main routes. Individuals under mandatory evacuation orders would likely encounter this congestion and may be delayed in arriving to their final destinations. However, this impact was only observed after the evacuees exited the mandatory evacuation zones.

The additional shadow evacuees caused significant congestion throughout the megaregion, delaying larger portions of the evacuating public. What was found by this research was that these delays did not immediately impede the evacuation of the mandatory evacuation area. However, once these evacuees exited this area and entered into the remainder of the megaregion, they were subject to the same congestion and delays as everyone else. The finding that the 90 percent and 100 percent clearance times were not impacted does not suggest that no impact had occurred, only that the impact did not affect the last 10 percent of the evacuees.

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