Using System Dynamics to Model Regional Healthcare Evacuations During A Hurricane

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1. ABSTRACT

Purpose: Planning for healthcare evacuations in the event of an impending hurricane presents unique challenges that cannot be addressed in the typical emergency preparedness exercise format. The applications of systems dynamics modeling can address this gap by allowing emergency managers to examine key variables that may drastically change the efficacy and efficiency of an evacuation.

Methods: A system dynamics model was designed for patients evacuating three hospitals in Savannah, Georgia to twelve receiving facilities across the state. Three key variables were assessed to illustrate aspects of emergency plans that can be tested, including patients evacuated, traffic congestion, and bed availability at identified receiving healthcare facilities.

Results: The baseline parameters of the simulation suggest a minimum 39 hours are required to safely evacuate hospital patients in Savannah prior to the initiation of contraflow on the primary evacuation route. The traffic congestion drastically reduces the lane flow capability, thus increasing the time and resources required for a successful evacuation. Decreased availability of beds at identified receiving healthcare facilities also increases the needed resources for a successful evacuation.

Conclusions*:* This model begins an intriguing foray into the application of systems dynamics techniques in managing healthcare evacuations and illustrates how such methods can be used to test emergency plans tat cannot be practiced and exercised in the real world.

2. INTRODUCTION

2.1. Evacuations

The prevalence of all emergency evacuations, including both general population and healthcare facilities, emphasizes` the need to design and develop plans that optimize efficiency and efficacy of the evacuation. According to the Sandia National Laboratory for the United States (US) Nuclear Regulatory Commission (NRC) (2005), on average, an evacuation of 1,000 or more people occurs approximately once every two to three weeks in the US. While almost three-quarters of those evacuations are small-scale (involving less than 5,000 people), there is a clear need to effectively plan for these evacuations (Dotson & Jones, 2005). While the exact prevalence of healthcare facility evacuations is unknown, by focusing solely on the healthcare response, emergency managers can begin to address challenges inherent to these facilities in order to make small imapcts on the success of the greater evacuation.

A healthcare facility interfaces with the general public during times of disaster or large-scale emergencies with partial or complete evacuations in one of two ways: internal and external hazards. In the event of a terrorist attack, pandemic outbreak, or some other external emergency, a healthcare facility can be called upon as a resource, to provide high-quality patient care for the greatest number of people, as the general population evacuates from the incident towards the hospital. Alternatively, the facility itself can be damaged due to internal hazards, such as a fire, flood, or spread of contamination, at which point the facility may need additional resources, such as another facility to receive evacuating patients in order to return to normal operating capability (Childers & Taaffe, 2010). Hurricanes and other natural disasters can cause both types of emergencies, depending on the proximity of the facility to the hazard. A facility may have to evacuate some or all of its patients either to make room for an incoming patient surge or because the facility itself lies in harm's way. Under these circumstances, less critical patients can be discharged early, but patients that need continued care must be transferred to other facilities capable of continuing their level of care (Childers & Taaffe, 2010). The emergency manager at a healthcare facility must therefore consider not simply just an available bed, but one that matches the care needs for each patient, which dramatically increases the logistical challenges faced in a healthcare evacuation.

Before a healthcare facility even begin to tackle the logistical challenges in an evacuation, the decision to evacuate presents its own challenges and considerations. For example, when a healthcare facility lies in the path of a hurricane, making the decision to evacuate involves factors different from those influencing the general population. Patients in these facilities represent a largely dependent population, relying on the direction and assistance from staff as well as the availability of appropriate transportation and other medical resources to evacuate effectively. Moreover, transporting patients has an inherent risk, as removing a patient from a stable environment for the duration of transportation between the two facilities introduces an adverse risk to patient outcomes (Childers & Taaffe, 2010). First hand accounts from Brunswick, Georgia suggest additional barriers must be acknowledged, including determining how to lock the emergency department door once the facility is empty and the psychological impacts on the healthcare providers at the facility. Given these considerations, the decision to evacuate a healthcare facility is not made lightly or without extensive consideration. As McGlown (1999) identified in her research, there are five categories that contribute to a healthcare facility's decision to evacuate: infrastructure impediments, event monitoring, time and risk factors, internal environment, and external environment. An emergency manager weighing such a decision must balance these considerations and consult with the prepared evacuation plan.

To address some of these challenges and considerations, every healthcare facility is required to have a plan for evacuation that should be reviewed and updated on a regular basis (Augustine & Schoettmer, 2005; Schultz, Koening, Auf der Heide, & Olson, 2005; Sternberg, Lee, & Huard, 2004). However, such plans are often only written to meet the standards set by accrediting agencies (McGlown, 1999). For example, the Occupational Safety and Health Administration (OSHA) requires all facilities to maintain an emergency action plan, which must include procedures for emergency evacuation under standard 1910.38 (United States Department of Labor, 2002). In contrast, The Joint Commission and Centers for Medicare and Medicaid Services (CMS) require "an emergency plan employing an all-hazards approach targeting capabilities and capacities essential to preparedness emergencies and disasters particular to the location of a provider" (The Joint Commission, 2017). Depending upon the guidelines to which a facility adheres, their plans may vary in holistic efficacy, resulting in potential vulnerabilities in the preparedness of these facilities.

The lack of historical hospital evacuation data further hinders emergency managers' efforts to examine previous healthcare evacuations in order to improve their own evacuation plans (Johhnson, 2006; Schultz et al., 2005; Sternberg et al., 2004). Sternberg et al. (2004) analyzed the causes of hospital evacuations between 1971 and 1999, but the lack of analysis of any evacuations in the 21st century results in a gap in the literature. Schultz et al. (2005) created a standardized data collection survey for hospital evacuations that included demographics, characteristics of the emergency plan, and decision making as well as patient movement during the event. However, it is difficult to tell if this survey has been implemented.

Even though a centralized database does not exist, examining significant events, such as previous hurricanes, provides key considerations to be addressed in planning for a healthcare evacuation. Certain types of emergencies, like hurricanes, may affect multiple local hospitals (Augustine & Schoettmer, 2005; Bovender & Carey, 2006; Sternberg et al., 2004). While local facilities should be identified to receive patients from facilities affected by an internal emergency, non-regional facilities should also be identified for external emergencies that may affect the whole community (Childers & Taaffe, 2010). Planners should also consider that widespread emergencies will also likely impact the availability of beds at previously identified receiving hospitals.

Prior significant incidents also suggest these emergencies likely place increased demand on transportation resources, such as ambulances, which emergency managers must address in their evacuation plans. Access to these resources has been continually identified as an issue during hospital evacuations (Dosa, Grossman, Wetle, & Mor, 2007; Hyer, Brown, Berman, & Polivka-West, 2006; Levinson, n.d.). For example, after Hurricane Katrina, it was found that in some cases, multiple facilities contracted with one or two ambulance providers, who could transport patients from any one of several of facilities, but not all facilities simultaneously (Murray-Tuite & Wolshon, 2013). Moreover, given the simultaneous evacuation of the general population and healthcare facilities, there is an increased demand for road capacity. Contraflow, a form of a reversible traffic operation in which one or more lanes of a divided highway are used for the movement of traffic in the opposing direction, was used for the first time on a large-scale during Hurricane Floyd in 1999 (American Association of State Highway and Transportation, 2018). The measure is effective as it can both immediately and significantly increase the directional capacity of a roadway without the time or cost required to plan, design, and construct additional plans. Moreover, the public generally views it as a positive measure due to its logical implementation of using resources as available (Murray-Tuite & Wolshon, 2013). However, when routes inbound to the evacuating facility are limited, this inhibits the ability of ambulances or other transportation resources to make multiple trips. An emergency manager must carefully balance the need for increased capacity for an optimized evacuation with the need for emergency resources to enter the evacuating area when making the decision to contraflow critical routes.

In order to assess whether or not these key considerations have been addressed, the competence of emergency plans are typically addressed through tabletop and full-scale exercises as a proxy for real world events. Under the Joint Commission requirement to regularly conduct exercises, hospitals typically carry out these exercises to become familiar with the sequence of events that needs to occur under these incidents (The Joint Commission, 2017; Tayfur & Taaffe, 2009). The Joint Commission requirement also instructs facilities to test the hazards most likely to affect the facility, as identified in the hazard vulnerability analysis. Depending upon the facility location, an evacuation may not be the most critical hazard for which to plan and test. However, in emergency preparedness exercises, facility emergency managers typically only have time to test a small number of scenarios using the standard exercises approach and are unable to fully practice an evacuation, which makes it difficult to assess the true efficacy of such plans. The exercises generally assume nature behaves according to a predicted scenario, when such a scenario is rarely the case in practice. Moreover, the goals of exercises are frequently to familiarize staff to the plan and build relationships amongst staff (Lurie et al., 2004). There is a lack of standard to ensure exercises truly test the validity of emergency operations plans or their ability to respond to scenarios outside of the expected outcomes (Manley et al., 2006). Simulations and models can begin to address some of these gaps by providing insight into potential improvements for existing plans.

2.2. Research in Modeling Evacuations

Simulations are virtual experiments carried out on a computer, based on a model designed around a specific system and problem. By adjusting variables, decision rules, and procedures, one can easily test various hypothesis to better understand that system's behavior (Mielczarek & Uziałko-Mydlikowska, 2012). In doing so, one is better equipped to predict its future behavior. Modeling and simulations are widely used in a variety of fields and disciplines, including healthcare expense optimization, traffic simulation, and surgeon training (Mielczarek & Uziałko-Mydlikowska, 2012; Sisiopiku Virginia P., 2007; Sutherland et al., 2006). However, such technology has had limited use in emergency management planning (Jain & McLean, 2003; Wang, Schyndel, Wainer, Rajus, & Woodbury, 2012). The quality of emergency plans can drastically increase by understanding the systems and its problems to such a degree.

Various researchers have attempted to model different aspects of evacuations, but the preponderance of this work focuses on the general population (Childers & Taaffe, 2010; Perry & Lindell, 1991; Sorensen, 1991). Li, Yang, and Wei (2006) combined traditional dynamic traffic flow modeling with a Geographic Information System (GIS)-based traffic modelling approach for an integrated emergency evacuation planning system, and Chen, Meaker and Zhan (2006) analyzed the unique challenges of a general population evacuation of the Florida Keys. These works built the foundation for the federally sponsored Hurrevac software. Administered by the Federal Emergency Management Agency (FEMA), the US Army Corps of Engineers (USACE), and the National Oceanic and Atmospheric Administration (NOAA) National Hurricane Center, Hurrevac software provides local emergency managers insight regarding the last possible time by which a general population evacuation could be initiated if it is to be completed before the arrival of the storm's hazards (Sea Island Software, Inc, 2018).

However, there is very little research addressing healthcare facility evacuations, as quantitative techniques (e.g. simulations) are largely unresearched for this population (Tayfur & Taaffe, 2009). The Agency for Healthcare Research and Quality (AHRQ) used to provide a web-based evacuation planning tool for healthcare facilities. An emergency manager at a healthcare facility could provide the number and types of available transportation resources as well as the number and types of patients to be evacuated. The model would then return the time and transportation resources needed for an effective evacuation, using the foundational assumption that the sickest patients are transferred to the closest facilities. However, this model was based on lapsed grant funding and is now currently archived in the AHRQ website (Agency for Healthcare Research and Quality, n.d.).

Of the literature that does address this need, Tayfur and Taaffe (2009) used stochastic modeling to examine nurse and vehicle transport requirements for the evacuation of all patients while minimizing cost within a pre-specified evacuation completion time. By using stochastic techniques, Tayfur and Taaffe were able to estimate the probability distributions of transport requirements by allowing for random variation in the inputs of their model (Tayfur & Taaffe, 2009). Duanmu, Taaffe, and Chowdhury (2010) presented perhaps the most sophisticated model for evacuation to date as their model simulates an external disaster that forces the general population and healthcare facilities to evacuate simultaneously. This traffic simulation model analyzes the interaction and effects on evacuation time, delays, and routes by testing various evacuation times (Duanmu et al., 2010). Ideally, healthcare facilities would be completely evacuated 24 hours prior to a general population evacuation order, which occurs 36 hours prior to storm landfall (Region J Healthcare Coalition, 2015). This model, therefore, represents a worst case scenario, rather than the scenario in the emergency plan. While a worst case scenario model ultimately allows an emergency manager know how to avoid such circumstances, a model designed around the intended emergency plan allows an emergency manager to assess its natural efficacy.

While both of these models provide critical insight into behavior during healthcare evacuations, neither addresses the additional constraints placed upon the system by multiple facilities evacuating. Both models assume a single hospital evacuates. Moreover, both models were developed prior to widespread implementation of contraflow polices, which radically change the time under which ambulances can successfully complete multiple trips for evacuating patients. The following paper introduces a fundamental system dynamics model that considers not only the unique feature of contraflowing the singular route out of Savannah, Georgia but also the impact of multiple hospitals evacuating to multiple receiving facilities around the state. System dynamics is a mathematical modeling technique to understand the nonlinear behavior of complex systems over time using features such as stocks, flows, feedback loops, and time delays (Rahim, Hawari, & Abidin, 2017). If researchers can learn more about healthcare facility evacuations, we can provide tools to aid emergency managers in their decision making before and during patient transfers. Moreover, insights provided by research can be incorporated into evacuation plans and training exercises as guidelines to help staff prepare for real-time decisions in any length of evacuation window (Childers & Taaffe, 2010).

3. MODEL METHODOLOGY

3.1. Model Environment

The simulations were performed in Vensim PLE 7.3.5 (Ventana Systems, Inc., 2017), a systems dynamics program developed by Ventana Systems, Inc. in Harvard, Massachusetts that is pubically available. This model defines the distribution of hospital patients from Savannah, Georgia to various receiving facilities across the rest of the state under an impending hurricane. For the purposes of clarity, all routes heading away from Savannah are described as outbound, while all routes heading towards Savannah are described as inbound. The simulations were conducted on an Apple MacBook Pro with a 2.9 GHz Intel Core i7 processor and 16 GB of RAM running under the Windows 10 operating system. The following subsections discuss in detail the computational components of each element in the model.

3.2. *Model Assumptions*

This design of this model is to introduce a principle concept of how such technology can be used in regional healthcare evacuations. In order to maintain some simplicity, three evacuating hospitals and twelve receiving facilities where chosen. The three evacuating hospitals were used to represent a regional healthcare evacuation, while the twelve receiving facilities were chosen to represent ranging locations from across the state. This model also focuses solely on ground ambulances, the number of which is not adjusted by Emergency Management Assistance Compact (EMAC) or federal contract resource availability. By default, the programming software sends ambulances to the receiving facilities in order of facilities listed. Therefore, this iteration of the model makes no analysis on the best order to choose receiving facilities, and assumes an alphabetical distribution. The model also ignores edge effects from other adjoining states that either may be under similar states of disaster or may be providing additional resources (as discussed previously through EMAC). Furthermore, as this model functions as simplistic as possible, patient beds are not affected by members of the general public arriving at either the evacuating or receiving facility in search of care. While these assumptions represent an ideal evacuation, they allow us to build a system that can illustrate the use of system dynamics in these circumstances.

3.3. Evacuating Savannah

In the event of a hurricane heading towards Georgia's Atlantic coast line, the entire population of the coast evacuates. For the purposes of this model, the authors focused on the evacuation of Savannah hospitals, acknowledging such an evacuation accounts for approximately 20% of the total number of patients requiring evacuation from the coast of Georgia by restricting bed availability at receiving facilities, as discussed in section 3.6. The staffed bed capacity of all acute care hospitals in Savannah is 1016 (Table 1) (American Hospital Directory, 2019). For a baseline assessment, the authors also assumed 80% of patients at these facilities can be discharged or evacuated by other means, such as personal vehicles, so 204 acute patients must be evacuated via ambulance to another facility for continued care.

Equation 1 was integrated to calculate the total number of ambulances available to transport patients out of Savannah. The "if then else" function indicates a three step consideration such that if the first condition is met, the second statement is followed; if the first condition is not met, the third statement is followed. In this equation, if there were no available ambulances in Savannah, the model chose the maximum of either zero or the sum of the flow rate of the inbound lanes to Savannah. If there were available ambulances in Savannah, the model merely integrated the sum of the inbound lanes minus the outbound lanes. The initial value of available ambulances in Savannah was varied. At the beginning of the model, 20 ambulances were placed in Savannah to transport patients. The model assumes one patient is transported per ambulance.

Equation 1. Number of available ambulances in Savannah.

3.4. Interstate 16 Lanes

When evacuating Savannah to the rest of the state of Georgia, almost all of the traffic must go through Interstate 16 (I-16). Running approximately 167 miles, this interstate runs two lanes each way from Macon, Georgia to Savannah, Georgia. In Hurricane Floyd, I-16 was contraflowed to increase the lane capacity for evacuation. When contraflow is implemented, the two inbound lanes are set to flow in the opposite direction such that four lanes can now depart Savannah, but no lanes enter. Contraflow ends approximately in Dublin, Georgia, 111 miles away from Savannah. The model is designed such that no traffic is able to return to Savannah once the pre-specified contraflow time, defined as hours prior to arrival of storm, is reached. Once I-16 has been contraflowed, any returning ambulances will be forced to use alternative routes that will greatly increase the return time. A more sophisticated and nuianced model could add alternative return routes; however, for the purposes of illustrating how such a simulation can illustrate a regional evacuation, the model focuses on hospital evacuation prior to contraflow.

Equation 2 represents the flow rate of each lane leaving Savannah, denoted as I-16 Outbound Lane 1 and I-16 Outbound Lane 2. If there were no ambulances in Savannah, the flow rate was set to zero. Otherwise, the flow rate was calculated by the average speed divided by the 111 miles between Savannah and Dublin and multiplied by the traffic congestion factor as well as the number of available ambulances split across each lane. In lieu of data that accurately reflects the traffic experienced during a hurricane evacuation for the Georgia coast, the traffic congestion factor is represented as a constant, which can be adjusted to represent what proportion of total lane capacity is achieved. For example, if the traffic congestion factor is set to 2, this indicates the lane flow is operating at half capacity, and if the congestion factor is set to 4, this indicates the flow is operating at a quarter of the lane's full capacity. This approximation allows the model to account for additional vehicles on the road as a potential hinderance to the efficiency of an evacuation.

Equation 2. I-16 Outbound Flow Rate

Equation 3 represents the flow rate of each lane returning to Savannah, denoted as I-16 Inbound Lane 1 and I-16 Inbound Lane 2. The model chose the lesser value, or the minimum, of average speed divided by the 111 miles between Savannah and Dublin, multiplied by the traffic congestion factor, and the total of each of the incoming routes returning from the receiving facilities divided across the two lanes. Each lane was normalized to half of the number of ambulances passing through the return point in Dublin. The pulse function was utilized to set the contraflow time such that the flow rate was set to zero after a certain number of hours elapsed in the simulation. The abbreviations preceding inbound and outbound refer to the specific flow rates for each receiving facility. Table 2 delineates each abbreviation for each hospital.

Equation 3. I-16 Inbound Flow Rate

3.5. Dublin Inbound and Outbound

As discussed previously, the point at which contraflow ends and normal traffic resumes on I-16 is approximately located approximately 111 miles from Savannah in Dublin. In order to account for contraflow, Dublin outbound and Dublin inbound refer to points where contraflow ends or resumes. There are two separate lane flows to ensure each ambulance is forced to a receiving hospital rather than bypassing in a smaller loop.

Equation 4 is integrated by Vensim to represent the number of ambulances at the end of the contraflow point. The “if then else” function indicates a three step consideration such that if the first condition is met, the second statement is followed; if the first condition is not met, the third statement is followed. If the value is less than or equal to zero, the model should choose the largest value of either zero or the sum of the lanes departing Savannah. If the value is greater than zero, Vensim integrates the sum of the negative values of each of the outbound flow rates. The abbreviations preceding inbound and outbound refer to the specific flow rates for each receiving facility. Table 2 delineates each abbreviation for each hospital.

Equation 4. Ambulances at Dublin Outbound

The integration of Equation 5 represents the number of ambulances returning to the contraflow point of I-16, is simply the addition of all of the returning ambulances from the receiving hospitals minus the I-16 flow rates returning to Savannah.

Equation 5. Ambulances at Dublin Inbound

3.6. Receiving Facilities

The State of Georgia has 103 non-federal, short-term, acute care hospitals that do not serve a specific population, such as veterans (American Hospital Directory, 2019). As an illustrative example, twelve receiving facilities were chosen (Table 2). These facilities represent the regional coordinating hospitals for 12 of the 14 healthcare coalitions across the State of Georgia. Of the two remaining coalitions, one represents the Georgia coast, which is evacuated under this simulation and therefore cannot receive patients. Transportation between Savannah and regional coordinating hospital in the other remaining healthcare coalition not included in this model, based in Waycross, Georgia, does not require I-16. For the purposes of simplifying the model, this facility was not included.

Each facility's bed availability was calculated by multiplying the reported staffed beds by the national average for maintained bed occupancy (American Hospital Directory, 2019). According to the Becker's Hospital Review, the national average for maintained bed occupancy is 65.4% (Ellison & Cohen, 2018). In discussions with hospital emergency managers in Georgia, this is a conservative estimate for the State of Georgia in that, anecdotally, Georgia hospitals tend to operate at 80-90% capacity. However, if normal surge guidelines are considered, to decompress at least 20% of current patients, the quoted statistic from Becker's Hospital Review roughly approximates the bed availability at receiving facilities, once decompression has occurred (Assistant Secretary for Preparedness and Response, 2019).

As previously discussed, patients evacuating Savannah account for approximately only 20% of the total number of patients evacuating the Georgia coastline. In order to adjust for the availability of beds, 20% of the available beds at the receiving facilities were dedicated to Savannah patients (Table 2).

The flow rate towards each facility was calculated by equation 6. The "if then else" function was again employed such that it indicates a three step consideration such that if the first condition is met, the second statement is followed; if the first condition is not met, the third statement is followed. In this equation, if the hospital received more than its designated bed capacity, the flow rate equaled zero. If the hospital still had availability, the flow rate reflected the calculated trip time. Table 3 indicates the values of equation 6 that are unique to each hospital.

Equation 6. Hospital outbound flow rate

Equation 7 then calculated the flow rate of ambulances departing the receiving facility to return to Savannah. The "if then else" function indicates a three step consideration such that if the first condition is met, the second statement is followed; if the first condition is not met, the third statement is followed. Under these conditions, if the hospital had no available ambulances or the flow rate into the hospital was zero, the flow rate returning to Savannah was also zero. However, if both were greater than zero, the rate simply reflected the calculated trip time. The inbound flow rate was also normalized by the number of ambulances at each facility to ensure only available ambulances are departing for Savannah. Similarly, table 3 indicates the relevant values in equation 7 that are unique to each hospital. As discussed in further detail in the following section, an hour was added to the trips leaving the receiving facility to account for time spent transferring the patient.

Equation 7. Hospital inbound flow rate

3.7. Trip Generation

To determine the duration of the transport of each patient, the distance between Savannah and each receiving facility was calculated using the shortest distance as identified by Google Maps (Google, n.d.) (Table 4). One hundred and eleven miles, representing the distance between Savannah and the point where contraflow ends in Dublin, were subtracted from the total distance to normalize the distance post-Dublin outbound flow, or the minimum number of non-contraflowed miles. Dividing each distance by 60 miles per hour resulted in the average one-way trip time for an ambulance. The inverse of this calculation produced the number of outbound trips that could be completed per hour. An hour was added to the return trip rate, noted as inbound trips per hour, in order to account for the time spent transferring the patient to the receiving facility.

4. RESULTS

4.1. Baseline Parameters

In the default state of the model, when the conditions in Table 5 are assigned, all 204 Savannah patients are evacuated in 39 hours. This result suggests, at minimum, healthcare facilities must begin evacuation at least 39 hours prior to landfall of the storm. It is worth noting the model calculations are based on landfall time of the storm's eye, not arrival of storm hazards. Given that safety of driving ambulances in winds greater than 35 mile per hour greatly decreases as wind speed increases, healthcare facilities must begin with enough time to be completed by the arrival of tropical storm force winds (Bureau of Emergency Medical Services, 2011). The contraflow time of 24 hours prior to landfall was chosen as an example; it may or may not accurately reflect the plans in the region. However, when testing their emergency evacuation plan, the local or healthcare facility emergency manager can adjust the parameters to more closely fit the intended plan.

Under the baseline conditions and assumptions (as described in Table 5) emergency managers can also gain insight as to how many patients can be evacuated by hour, should the number of patients needing evacuation be greater than expected. Table 6 displays these cumulative results every 12 hours with no contraflow time to illustrate the uninhibited evacuation capability.

4.2. Congestion Factor

As seen in Hurricane Floyd in 1999, evacuation of the Georgia coast leads to extensive bumper-to-bumper traffic on I-16 (Chatham EMA, 1999). The impact of congestion can drastically impact the ability of ambulances to reach the receiving facilities and return to Savannah to transport additional patients. Table 7 displays the number of patients evacuated in twelve-hour increments with double and quadruple rates of congestion, reducing I-16 outbound flow to half and a quarter of its capacity respectively. It assumes contraflow happens 24 hours prior to storm arrival and thus no more patients can be evacuated due to a lack of incoming ambulances. The table also shows the exact hour in which the minimum 204 patients are evacuated from Savannah. When the lane flow is reduced to half its capacity, it takes an additional eight hours to successfully evacuate all patients. Interestingly, congestion does not have a linear impact on successful patient evacuation, as emphasized by the fact that congestion four times normal levels creates only a one-hour delay in successful patient evacuation, as compared to congestion two times normal levels.

4.3. Available Bed Capacity

While the national average for maintained bed capacity is 65.4%, the true capacity at each individual hospital ebbs and flows with daily management. As suggested below, changing the bed availability drastically changes the system's ability to effectively evacuate all 204 patients from Savannah.

Table 8 shows the bed availability at each of the twelve sample receiving facilities, varying the percent occupancy of total staffed beds. As previously discussed, only 20% of the available beds are listed, in order to account for the fact that Savannah evacuating represents approximately 20% of the total number of patients needing placement. Table 9 illustrates the results of such limitations in bed availability. If the receiving facilities are operating at 50% capacity, successful evacuation is completed within 34 hours, five hours less than if the facilities were operating at the national average. In contrast, if the receiving facilities are operating at 80% capacity, successful evacuation cannot be completed under the baseline parameters prior to contraflow.

5. DISCUSSION

5.1. *Analysis of Results*

The proposed model provides illuminating insight into hurricane evacuation planning, particularly when considering community-wide impacts and policies such as contraflow. Under standard assumptions (Table 5), evacuating the three hospitals based in Savannah, Georgia requires 39 hours to complete. The duration of such an evacuation drastically increases with congestion on I-16 or with decreased availability of beds at receiving facilities. These circumstances then warrant contingency plans to be added to the base evacuation plan, to address when certain elements may not execute exactly as planned.

In their analysis, Duanmu, Taaffe, and Chowdhury (2010) found that a hospital evacuation must start at least 12 hours prior to the mandatory evacuation order, typically issued 24-hours prior to landfall of the storm. Their model focuses on one hospital evacuating Charleston, South Carolina, while this model examines three hospitals evacuating Savannah, Georgia. Moreover, their model focuses on strict mesoscopic traffic concepts, whereas this model uses a congestion factor constant to account for traffic. The final significant difference in the two models is that while this model assumes hospitals are the receiving facilities, Duanmu, Taaffe, and Chowdhury choose designated shelters as the receving facilities. While these models differ in their methods and fundamental assumptions, they yield similar results in that healthcare evacuations must begin approximately two days prior to the landfall of the storm's eye.

As mentioned previously, the model described here counts down to the landfall of the storm, rather than the arrival of tropical storm force winds (the point at which ambulances can no longer be safely operated). As such, emergency managers should be cognizant of just how early healthcare evacuations must be triggered in the event of a potential hurricane. The arrival of such winds varies by storm, so emergency managers must closely monitor the forecasts provided by the National Hurricane Center to determine the appropriate time to evacuate. Given the relatively recent introduction of publically available forecasting for arrival of tropical storm force winds, there exists a gap in the literature for average time of arrival of such winds (National Hurricane Center, 2017). Moreover, as Tayfur and Taaffe (2009) elucidate, the decision to evacuate a healthcare facility must be made as early as possible in order to minimize cost and maximize efficiency of resource utilization. Given the uncertainty frequently seen in storm predictions, future research should examine the impact of a changing path of the storm in resources required for a safe and successful evacuation. By fine tuning the simulation methodology available, academia can begin to provide emergency managers with useful data to make the challenging decision to evacuate healthcare facilities.

Our model easily generates an approximation of potential patients evacuated as time of landfall of the storm gets closer, thus providing emergency managers with data to aid their decision in choosing a contraflow time. In the event the patients that need continued care during an evacuation from Savannah exceed the typical patient census, the model easily generates an hourly approximation of patients evacuated as the storm gets closer to landfall, providing emergency managers with data to aid their decision in choosing a time to contraflow I-16. Noteably, this model has the capacity to flex the number of patients needing evacuation, a critical aspect when considering the varying nature of the patient census at hospitals. Neither the simulation conducted by Tayfur and Taaffe (2009) nor the one conducted by Duanmu, Taaffe, and Chowdhury (2010) focus on patient counts; rather, they both focus on categories of patients to be evacuated. While their respective models provide insight into optimizing the cost of evacuation and traffic analysis, this model provides emergency managers with approximate numbers of patients that can by evacuated on an hourly basis.

Given historical examples of the extreme congestion seen in evacuating the Georgia coast, congestion on I-16 can dramatically reduce the efficiency of a healthcare evacuation via ground transportation. If the flow of each lane of I-16 is reduced to a quarter of its regular capacity due to congestion, an additional eleven hours are required to evacuate all of the patients requiring continued care, increasing the total evacuation time to 48 hours. Further analysis and more sophisticated modeling, such as the technique utilized by Duanmu, Taaffe, and Chowdhury (Duanmu et al., 2010), could account for the realistic traffic patterns during a hurricane evacuation, including motor vehicle collisions and subsequent standstill.

Finally, the suggested model also provides insight as to the impact of bed availability of receiving facilities. If the receiving hospitals are operating below the national average for bed occupancy at a 50% utilization rate, successful evacuation of Savannah patients can be completed within 34 hours. However, if occupancy increases to 80% of staffed beds, then the 204 Savannah patients cannot be evacuated under the baseline parameters. Under such circumstances, additional facilities would need to be identified as potential receiving facilities or alternative transportation resources would need to be utilized, such as air ambulances. Additionally, the capacity of healthcare facilities to receive patients is at least partially dependent upon the ability to match care specialty at the evacuating facility and the receiving facility on a patient level. While acute care needs can certainly be managed at a variety of facilities, the requirements for continuing care can greatly increase the complexity of a healthcare facility evacuation (Taaffe, Kohl, & Kimbler, 2005). Current literature surrounding healthcare evacuation simulation does not account for availability at receiving facilties; it generally assumes there is always availability for a patient. However, Tayfur and Taaffe (2009) group patients into relative acuity levels. Further iterations of such a model should incorporate a similar distinguishment of patient types so as to realistically represent how hospital emergency managers choose receiving facilities for each patient.

5.2. *Limitations*

There are several limitations to this model. Perhaps most obviously, the model only includes three evacuating hospitals and twelve receiving facilities. In reality, there is a significant increase in the number of both evacuating and receiving healthcare facilities. As previously mentioned, there are more than one hundred non-federal, short-term, acute care hospitals that admit the general population across the State of Georgia (American Hospital Directory, 2019). These numbers do not include other healthcare facilities that would need to evacuate, nor ones that could receive patients, such as skilled nursing facilities. While bed availability has been adjusted in an attempt to correct for this difference, some residual difference likely remains. Additionally, the model utilizes a time step of one hour. Given the output calculations are integrations and the duration of the model is 96 hours, the number of ambulances at any location is an approximation. To improve the exactness of these calculations, the time step would need to be reduced as much as possible in future iterations of the model. The model also treats ambulances and evacuated patients as continuous variables rather than discrete ones. As a result, the ambulances are sent simultaneously without delay in Savannah, when, in reality, an extensive, staggered delay likely exists. When interpreting the results of the model, the end user should understand these results are approximations and guidelines rather than absolute evacuation times. Finally, this model stops once contraflow is ordered as return routes to Savanna are radically altered. Future research should address this by adding the return routes with extended trip times. Nonetheless, in lieu of being able to exercise evacuation plans, using systems dynamics modeling illustrates an exciting and innovative way to test the validation of intended evacuation emergency plans. This technology can ultimately provide emergency managers a distinctive insight into the bariers and challenges seen in healthcare evacuations impacting an entire region or state, thus aiding them in improving their planning and decision making.

6. FIGURES AND TABLES

Table 1. Savannah hospitals and associated number of staffed beds.

Hospital Name	**Staffed Beds**
Memorial University Medical Center	527
Saint Joseph's Hospital	243
St. Joseph's/Candler Hospital	246
Total	1016

Table 2. Identified receiving facilities and associated bed availability.

Hospital Name	Hospital Abbreviation	Staffed Beds	Occupied Beds	Available Beds	Available Beds for Savannah Patients
Augusta University Medical Center	AUMC	499	326	172	34
Fairview Park Hospital	FPH	160	104	55	11
Floyd Medical Center	FMC	300	196	103	20
Grady Memorial Hospital	GMH	961	628	332	66
Hamilton Medical Center	HMC	272	177	94	18
Medical Center Navicent Health	MCNH	597	390	206	41
Northeast Georgia Medical Center Gainesville	NGMCG	879	574	304	60
Phoebe Putney Memorial Hospital	PPMH	433	283	149	29
Piedmont Athens Regional Medical Center	PARMC	357	233	123	24
Piedmont Columbus Regional - Midtown Campus	PCRMC	276	180	95	19
Tift Regional Medical Center	TRMC	181	118	62	12
WellStar Kennestone Hospital	WKH	662	432	229	45

Table 3. Inputs for hospital-specific flow rates

Hospital Name	Available Beds for Savannah Patients	Outbound trips per hour	Inbound trips per hour
Augusta University Medical Center	34	2.31	0.70
Fairview Park Hospital	11	7.50	0.88
Floyd Medical Center	20	0.29	0.22
Grady Memorial Hospital	66	0.43	0.30
Hamilton Medical Center	18	0.26	0.21
Medical Center Navicent Health	41	1.09	0.52
Northeast Georgia Medical Center Gainesville	60	0.32	0.24
Phoebe Putney Memorial Hospital	29	0.53	0.34
Piedmont Athens Regional Medical Center	24	0.55	0.35
Piedmont Columbus Regional - Midtown Campus	19	0.45	0.31
Tift Regional Medical Center	12	1.03	0.51
WellStar Kennestone Hospital	45	0.38	0.27

Table 4. Ambulance trips per hour for each receiving facility.

Hospital Name	Total distance from Savannah	Minimum number of non-Contraflowed miles	One-way trip time (hours)	Outbound trips per hour	Inbound trips per hour
Augusta University Medical Center	137	26	0.43	2.31	0.70
Fairview Park Hospital	119	8	0.13	7.50	0.88
Floyd Medical Center	319	208	3.47	0.29	0.22
Grady Memorial Hospital	249	138	2.30	0.43	0.30
Hamilton Medical Center	339	228	3.80	0.26	0.21
Medical Center Navicent Health	166	55	0.92	1.09	0.52
Northeast Georgia Medical Center Gainesville	298	187	3.12	0.32	0.24
Phoebe Putney Memorial Hospital	225	114	1.90	0.53	0.34
Piedmont Athens Regional Medical Center	221	110	1.83	0.55	0.35
Piedmont Columbus Regional - Midtown Campus	245	134	2.23	0.45	0.31
Tift Regional Medical Center	169	58	0.97	1.03	0.51
WellStar Kennestone Hospital	270	159	2.65	0.38	0.27

Table 5. Variables for model's baseline conditions and assumptions

Variable	**Value**
Patients to Evacuate	204 patients
Contraflow Time	24 hours prior to landfall
I-16 Speed	55 miles per hour
Remaining route speed	60 miles per hour
Number of ambulances available	20 ambulances
Congestion Factor	1 (no congestion)

Table 6. Number of patients evacuated under baseline conditions identified in Table 5 without contraflow

Time to Hurricane (hours)	**96**	**84**	**72**	**60**	**48**	**36**	**24**	**12**	**0**
Evacuated Patients:	0	69	140	192	236	262	283	297	311

Table 7. Number of patients evacuated under varying levels of congestion. Cells highlighted in yellow represent the time at which all 204 patients are successfully evacuated from Savannah.

Time to Hurricane (hours)	**96**	**84**	**72**	**60**	**57**	**49**	**48**	**36**	**24**
Evacuated Patients (No congestion)	0	69	140	192	205	233	236	262	283
Evacuated Patients (x2 congestion)	0	37	100	157	170	204	208	244	269
Evacuated Patients (x4 congestion)	0	30	93	152	166	200	204	242	269

Table 8. Bed availability for evacuating Savannah patients, varied by occupancy of staffed beds at each receiving facility.

Hospital Name	**50% Occupancy, Number of Beds Available**	**65.4% Occupancy, Number of Beds Available**	**80% Occupancy, Number of Beds Available**
Augusta University Medical Center	49	34	19
Fairview Park Hospital	16	11	6
Floyd Medical Center	30	20	12
Grady Memorial Hospital	96	66	38
Hamilton Medical Center	27	18	10
Medical Center Navicent Health	59	41	23
Northeast Georgia Medical Center Gainesville	87	60	35
Phoebe Putney Memorial Hospital	43	29	17
Piedmont Athens Regional Medical Center	35	24	14
Piedmont Columbus Regional - Midtown Campus	27	19	11
Tift Regional Medical Center	18	12	7
WellStar Kennestone Hospital	66	45	26

Table 9. Number of patients evacuated with varying bed capacity at receiving facilities. Cells highlighted in yellow represent the time at which all 204 patients are successfully evacuated from Savannah.

Time to Hurricane (hours)	**96**	**84**	**72**	**62**	**60**	**57**	**48**	**36**	**24**	**12**	**0**
Evacuated Patients (50% full)	0	64	151	204	213	226	265	316	352	357	357
Evacuated Patients (65.4% full)	0	69	140	183	192	205	236	262	283	286	286
Evacuated Patients (80% full)	0	50	105	138	143	149	164	178	191	193	193

7. REFERENCES

Agency for Healthcare Research and Quality. (n.d.). Mass Evacuation Transportation Model [Archive]. Retrieved March 31, 2019, from Mass Evacuation Transportation Model website: https://archive.ahrq.gov/prep/massevac/

American Association of State Highway and Transportation. (2018). *A Policy on Geometric Design of Highways and Streets* (7th edition). American Association of State Highway and Transportation Officials.

American Hospital Directory. (2019). American Hospital Directory - Individual Hospital Statistics for Georgia. Retrieved April 1, 2019, from https://www.ahd.com/states/hospital_GA.html

Assistant Secretary for Preparedness and Response. (2019, April 20). Hospital Surge Capacity and Immediate Bed Availability Topic Collection | Technical Resources | TRACIE. Retrieved April 22, 2019, from https://asprtracie.hhs.gov/technical-resources/58/hospital-surge-capacity-and-immediate-bed-availability/56

Augustine, J., & Schoettmer, J. T. (2005). Evacuation of a Rural Community Hospital: Lessons Learned From an Unplanned Event. *Journal of Emergency Nursing*, *3*(3), 68–72. https://doi.org/10.1016/j.dmr.2005.05.005

Bovender, J. O., & Carey, B. (2006). A week we don’t want to forget: lessons learned from Tulane. *Frontiers of Health Services Management*, *23*(1), 3–12; discussion 25-30.

Bureau of Emergency Medical Services. (2011). *EMS Information Bulletin 2011-12*. Retrieved from Pennsylvania Department of Healthh website: http://pehsc.org/wp-content/uploads/2014/05/EMSIB-2011-012_Wind-Effects-on-Amb.pdf

Chatham EMA. (1999). *1999 Hurricane Floyd After Action Report*. Retrieved from https://www.chathamemergency.org/archived/1999/floyd/1999%20Floyd%20AAR.pdf

Chen, X., Meaker, J. W., & Zhan, F. B. (2006). Agent-Based Modeling and Analysis of Hurricane Evacuation Procedures for the Florida Keys. *Natural Hazards*, *38*(3), 321. https://doi.org/10.1007/s11069-005-0263-0

Childers, A. K., & Taaffe, K. M. (2010). Healthcare Facility Evacuations: Lessons Learned, Research Activity, and the Need for Engineering Contributions. *Journal of Healthcare Engineering*, *1*(1), 125–140. https://doi-org.proxy-remote.galib.uga.edu/10.1260/2040-2295.1.1.125.

Dosa, D. M., Grossman, N., Wetle, T., & Mor, V. (2007). To Evacuate or Not to Evacuate: Lessons Learned From Louisiana Nursing Home Administrators Following Hurricanes Katrina and Rita. *Journal of the American Medical Directors Association*, *8*(3), 142–149. https://doi.org/10.1016/j.jamda.2006.11.004

Dotson, L. J., & Jones, J. (2005). *NRC: Identification and Analysis of Factors Affecting Emergency Evacuations: Main Report*. Retrieved from https://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr6864/v1/

Duanmu, J., Taaffe, K. M., & Chowdhury, M. (2010). Minimizing Patient Transport Times during Mass Population Evacuations - Jun Duanmu, Kevin Taaffe, Mashrur Chowdhury, 2010. *Journal of the Transportation Research Board*, *2196*(1), 150–158.

Ellison, A., & Cohen, J. K. (2018, June 25). Becker's Hospital Review. Retrieved April 1, 2019, from 224 hospital bechmarks | 2018 website: https://www.beckershospitalreview.com/lists/224-hospital-benchmarks-2018.html

Google. (n.d.). Google Maps. Retrieved March 1, 2019, from Google Maps website: https://www.google.com/maps/

Hyer, K., Brown, L. M., Berman, A., & Polivka-West, L. (2006). Establishing And Refining Hurricane Response Systems For Long-Term Care Facilities. *Health Affairs*, *25*(5), w407–w411. https://doi.org/10.1377/hlthaff.25.w407

Jain, S., & McLean, C. (2003). Simulation for Emergency Response: A Framework for Modeling and Simulation for Emergency Response. *Proceedings of the 35th Conference on Winter Simulation: Driving Innovation*, 1068–1076. Retrieved from http://dl.acm.org/citation.cfm?id=1030818.1030960

Johhnson, C. W. (2006). *Using Computer Simulations to Support A Risk-Based Approach for Hospital Evacuation*. Retrieved from http://www.dcs.gla.ac.uk/~johnson/papers/G-HES.PDF

Levinson, D. R. (n.d.). NURSING HOME EMERGENCY PREPAREDNESS AND RESPONSE DURING RECENT HURRICANES. *Department of Health and Human Services | Office of Inspector General*, 48.

Li, Q., Yang, X. K., & Wei, H. (2006). Integrating Traffic Simulation Models with Evacuation Planning System in a GIS Environment. *2006 IEEE Intelligent Transportation Systems Conference*, 590–595. https://doi.org/10.1109/ITSC.2006.1706805

Lurie, N., Wasserman, J., Stoto, M., Myers, S., Namkung, P., Fielding, J., & Valdez, R. B. (2004). Local Variation In Public Health Preparedness: Lessons From California. *Health Affairs*, *23*(Suppl1), W4-341. https://doi.org/10.1377/hlthaff.W4.341

Manley, W. G., Furbee, P. M., Coben, J. H., Smyth, S. K., Summers, D. E., Althouse, R. C., … Helmkamp, J. C. (2006). Realities of Disaster Preparedness in Rural Hospitals. *Disaster Management & Response*, *4*(3), 80–87. https://doi.org/10.1016/j.dmr.2006.05.001

McGlown, K. (1999). *Determinants of the Evacuation of Healthcare Facilities* (PhD Dissertation). University of Alabama at Birmingham.

Mielczarek, B., & Uziałko-Mydlikowska, J. (2012). Application of computer simulation modeling in the health care sector: a survey. *SIMULATION*, *88*(2), 197–216. https://doi.org/10.1177/0037549710387802

Murray-Tuite, P., & Wolshon, B. (2013). Evacuation transportation modeling: An overview of research, development, and practice. *Transportation Research Part C: Emerging Technologies*, *27*, 25–45. https://doi.org/10.1016/j.trc.2012.11.005

National Hurricane Center, N. (2017). New National Hurricane Center Capabilities Introduced this Hurricane Season. Retrieved April 23, 2019, from https://www.weather.gov/news/172811-hurricane-season

Perry, R. W., & Lindell, M. K. (1991). The Effects of Ethnicity on Evacuation Decision-Making. *International Journal of Mass Emergencies and Disasters*, *9*(1), 47–68.

Rahim, F. H. A., Hawari, N. N., & Abidin, N. Z. (2017). Supply and demand of rice in Malaysia: A system dynamics approach. *International Journal of Supply Chain Management*, *6*, 234–240.

Region J Healthcare Coalition. (2015). *Region J Strategic Evacuation Timeline*.

Sandia National Laboratories. (2005). *Identification and Analysis of Factors Affecting Emergency Evacuations: Main Report* (p. 61). Washington, DC: U.S. Nuclear Regulatory Commission Office of Nuclear Security and Incident Response.

Schultz, C. H., Koening, K. L., Auf der Heide, E., & Olson, R. (2005). Benchmarking for hospital evacuation: a critical data collection tool. *Prehospital and Disaster Medicine*, *20*(5), 331–342. https://doi.org/10.1017/S1049023X00002806

Sea Island Software, Inc. (2018, June 4). Hurrevac Support Site. Retrieved April 1, 2019, from Hurrevac Home website: http://www.hurrevac.com/

Sisiopiku Virginia P. (2007). Application of Traffic Simulation Modeling for Improved Emergency Preparedness Planning. *Journal of Urban Planning and Development*, *133*(1), 51–60. https://doi.org/10.1061/(ASCE)0733-9488(2007)133:1(51)

Sorensen, J. (1991). When Shall We Leave Factors Affecting the Timing of Evacuation Departures. *International Journal of Mass Emergencies and Disasters*, *9*, 153–196.

Sternberg, E., Lee, G. C., & Huard, D. (2004). Counting crises: US hospital evacuations, 1971-1999. *Prehospital and Disaster Medicine*, *19*(2), 150–157.

Sutherland, L. M., Middleton, P. F., Anthony, A., Hamdorf, J., Cregan, P., Scott, D., & Maddern, G. J. (2006). Surgical Simulation. *Annals of Surgery*, *243*(3), 291–300. https://doi.org/10.1097/01.sla.0000200839.93965.26

Taaffe, K., Kohl, R., & Kimbler, D. (2005, January 1). *Hospital evacuation: Issues and complexities*. 943–950. https://doi.org/10.1109/WSC.2005.1574343

Tayfur, E., & Taaffe, K. (2009). Simulating hospital evacuation—the influence of traffic and evacuation time windows. *Journal of Simulation*, *3*(4), 220–234. https://doi.org/10.1057/jos.2009.16

The Joint Commission. (2017, September 13). Revised EM standards mesh with CMS final rule on Emergency Management. Retrieved April 1, 2019, from http://www.jointcommission.org/issues/article.aspx

United States Department of Labor. (2002, November 7). Emergency action plans. - 1910.38 | Occupational Safety and Health Administration. Retrieved April 1, 2019, from https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_id=9726&p_table=standards

Ventana Systems, Inc. (2017). Vensim PLE Software (Version 7.3.5). Retrieved from https://vensim.com/

Wang, S., Schyndel, M. V., Wainer, G., Rajus, V. S., & Woodbury, R. (2012). DEVS-based Building Information Modeling and simulation for emergency evacuation. *Proceedings of the 2012 Winter Simulation Conference (WSC)*, 1–12. https://doi.org/10.1109/WSC.2012.6465087